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DISPERSION OF COPPER FROM THE SAN MANUEL COPPER DEPOSIT, PINAL COUNTY, ARIZONA.[1]

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ABSTRACT.

At San Manuel, near Tucson, Arizona, recent churn drilling has blocked out large reserves of low-grade "porphyry copper" ore. This virgin deposit has a small outcrop and seems ideally suited for a geochemical study of the dispersion pattern produced by weathering in a desert climate. Samples of soils, alluvium, ground water, and vegetation were analyzed for copper. To avoid grinding, to accentuate differences in copper concentration, and to decrease sampling error, sampling was confined to the silt and clay fraction of the soil and alluvium. A sensitive field test for copper, using hydrochloric acid for a digestant and dithizone for copper determination, proved both quick and reliable.

The results of the study show that at present little copper from the ore body dissolves in the ground water or runoff, and also that very little is taken up by plants growing on the ore outcrop. For this reason, prospecting for similar deposits by the sampling and analysis of ground water or vegetation is unlikely to be fruitful. A study of plant ecology, however, shows

[1] Published by permission of the Director, U. S. Geological Survey.

that certain plant species grow preferentially on outcrops of copper ore and may be useful as indicators of ore.

Chrysocolla along joints carries most of the copper in the oxidized zone. The chrysocolla is slowly disintegrated mechanically as the rock weathers and enters the fine fraction of the soil. Slope wash and soil creep carry the copper along with the other soil materials into the nearby washes, where they are incorporated in the alluvium and swept downstream during floods. Abrasion probably continues to concentrate the copper in the fines, but the net change downstream is a decrease in copper content caused by dilution.

As copper can now be readily determined by chemical analysis in the field, analysis of soil and alluvium seems to be one of the best geochemical methods of prospecting for copper in a desert environment. Wherever appreciable copper is found in alluvium or soils, upstream or upslope sampling can be used to trace the copper back to its source.

INTRODUCTION.

Prospecting for metallic ore deposits by chemical methods is a comparatively new application of geochemistry, and prior to 1947 nearly all investigations of "geochemical prospecting" were made in Europe.[2] Recently the U. S. Geological Survey has undertaken a program of investigations designed to determine what happens to the ore metals during weathering and erosion, and what sampling techniques, analytical methods, and natural conditions are most favorable for chemical prospecting. The investigation described in this paper is a part of the program.

One difficulty in the development of geochemical prospecting methods is the scarcity of undisturbed ore deposits to use as test areas; exploratory or routine mining operations may radically change the metal content of the soil and waters nearby, and analyses of these materials would give little clue to the original chemical conditions. The recent discovery and subsequent drilling of the San Manuel ore body 40 miles north of Tucson, Arizona, has offered an unusual opportunity to study the chemical weathering of a copper deposit before it is disturbed by mining.

The proved reserves of more than 400 million tons of low-grade but commercial ore make the San Manuel copper deposit one of the most important potential sources of copper in the West. Only a small area of low-grade oxidized ore crops out at the surface, and gives little hint of the tremendous body lying below. A few holes were drilled many years ago, and the results discouraged further exploration. In March 1943, after a brief study of the area, B. S. Butler and N. P. Peterson of the U. S. Geological Survey recommended exploration by drilling to ascertain the size and tenor of the deposit and its suitability as a wartime source of copper. Seventeen churn-drill holes, subsequently drilled by the U. S. Bureau of Mines, established the general character of the deposit and revealed the presence of a large body of ore. Much of the copper-bearing area was then acquired by the Magma Copper Co., which put

[2] Rankama, Kalervo, Some recent trends in prospecting—chemical, biogeochemical, and geobotanical methods: Mining and Metallurgy, vol. 28, pp. 282–284, 1947.

Sergeev, F. A., Fiziko-Himicheskii Metod Poiskov Rudugh Zoleskei (Geochemical method of prospecting for ore deposits), Materially Vsesoiuznogo Naucho-Issledovatelnogo Geologicheskoso Institute Geofizika-Skornik Fascile 9–10, p. 3–54. Translation from Russian by V. P. Sokoloff in files of U. S. Geological Survey, 1941.

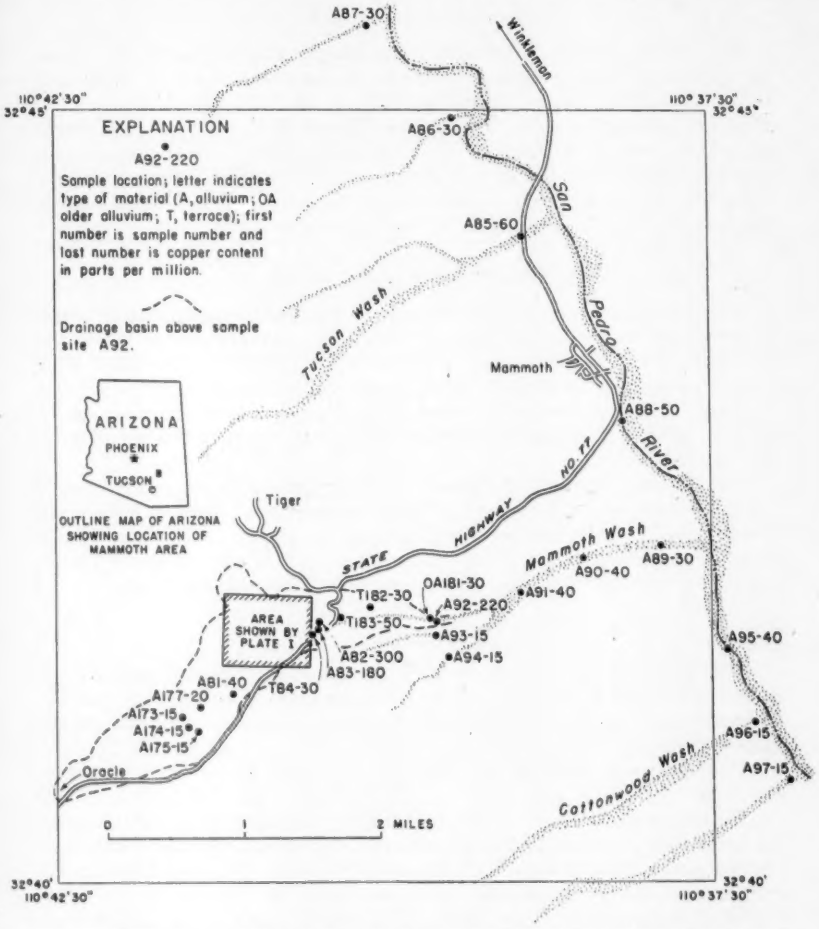


FIG. 1. Outline map of Mammoth area, showing location of San Manuel district and sampling sites.

down 89 additional holes to delimit the size, position, shape, and grade of the ore body. This virgin deposit with its small outcrop of ore seemed ideally suited to a geochemical study of the dispersion pattern of copper in a semiarid climate. A geochemical field study was made in the winter of 1947–1948, and two techniques were tried out that showed promise as rapid methods of prospecting large areas. They are chemical analysis of alluvium and a study of plant ecology—techniques that apparently have received too little attention.

ACKNOWLEDGMENTS.

The writers are greatly indebted to the Magma Copper Co. for permitting and facilitating the investigation. Thanks are due also to the U. S. Bureau of Mines, and to the Arizona Bureau of Mines at the University of Arizona for office and laboratory space. Dr. George Darrow of the Botany Department at the University of Arizona was invaluable in the study of plant ecology, generously giving his time for field conference and for identifying plant specimens. The constructive suggestions of many members of the U. S .Geological Survey also have been very helpful in forwarding the project.

PHYSIOGRAPHY AND CLIMATE.

The San Manuel copper deposit is in the Mammoth mining district about 40 miles north-northeast of Tucson, Arizona (Fig. 1). The deposit lies on the east flank of the Black Hills at an altitude of about 3,500 feet. The Black Hills in this locality show moderately strong local relief and are intricately dissected by sharp, V-shaped arroyos. A short distance eastward the arroyos coalesce and pass through an old, partly dissected alluvial slope deposit before emptying into the San Pedro River.

The climate is typical of the Basin and Range section of Arizona. Rainfall is low, probably averaging about 10 inches annually, and rarely is sufficiently concentrated to cause surface runoff through the arroyos. The winters are mild and the summers hot. The vegetation, as can be seen from the photographs, includes many varieties of cacti and other typical desert plants.

GEOLOGY.

The older rock or basement complex that contains the San Manuel copper deposit includes Precambrian (?) quartz monzonite, its related aplite, and a later monzonite porphyry.[3] These rocks extend northward into the adjoining Mammoth mining district [4] and crop out in a horst surrounded by mid-Tertiary (?) volcanic rocks and the late Tertiary and early Quaternary Gila conglomerate.

The quartz monzonite is a coarse-grained slightly porphyritic rock containing moderately abundant subhedral pink orthoclase phenocrysts set in a coarse-grained groundmass of quartz, oligoclase, and biotite. It is cut by medium-grained pinkish-gray aplite dikes, and both rocks are intruded by irregular masses of monzonite porphyry and by diabase dikes that are both earlier than the ore. About 50 percent of the monzonite porphyry is dark-gray felsitic groundmass; the phenocrysts are chiefly andesine laths and euhedral green biotite crystals. Along the north edge of the outcrop of the San Manuel ore

[3] Chapman, L. T., San Manuel Copper Deposit, Pinal County, Arizona: U. S. Bur. Mines, Rept. Inv. 4108, 1947.
Schwartz, G. M., Geology of the San Manuel area, Pinal County, Arizona: U. S. Geol. Survey Strategic Mineral Investigation, Preliminary maps 3–180, 1945.

[4] Peterson, N. P., Geology and ore deposits of the Mammoth mining camp area, Pinal County, Arizona (1938): Arizona Bur. Mines and Geol. Ser. 11, Bull. 144, pp. 1–63, 1938.
Schwartz, G. M., Hydrothermal alteration in the "porphyry copper" deposits: ECON. GEOL., vol. 42, pp. 319–352, 1947.

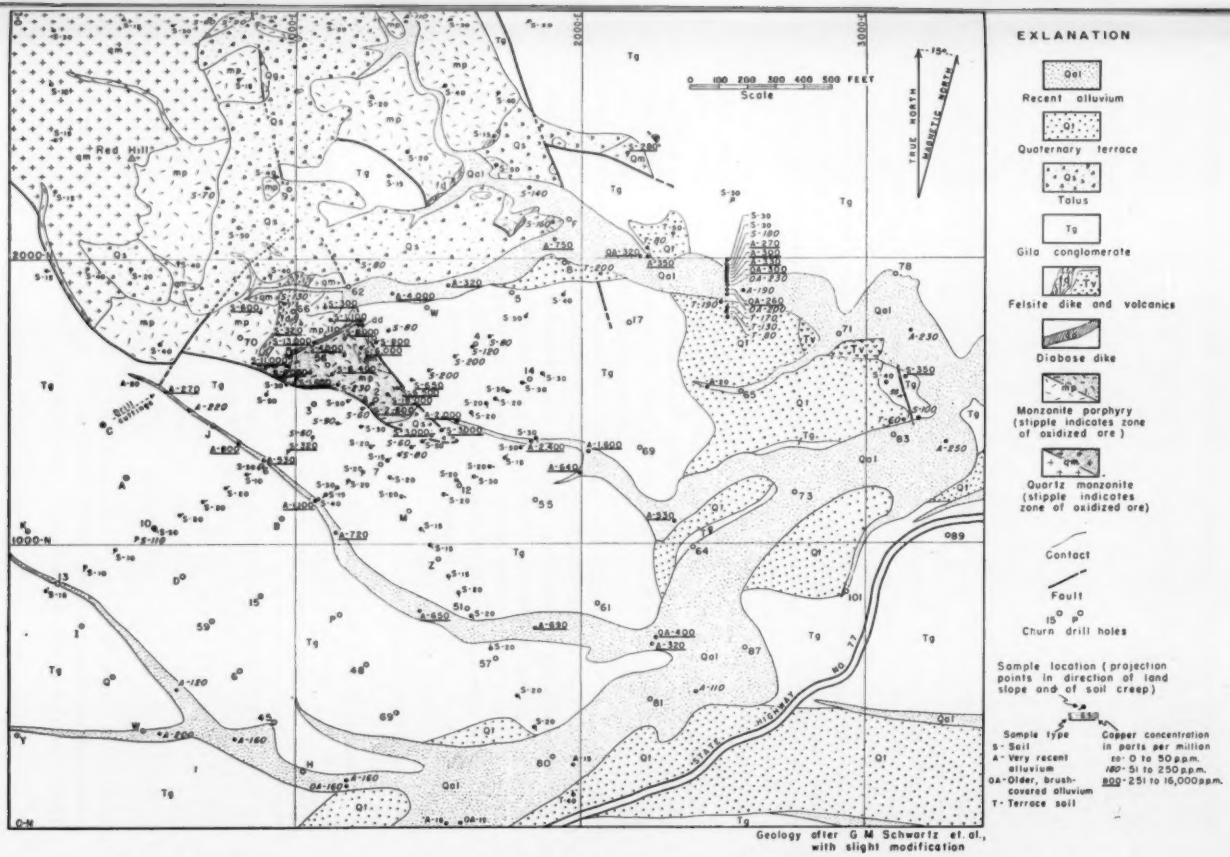


FIG. 2. Geologic and geochemical map of the San Manuel copper deposit and vicinity, Pinal County, Ariz.
(Sample location key on p. 504.)

body the basement rocks are cut by a felsite dike that is slightly altered but is later than the ore.

Schwartz recognizes four zones of alteration in the basement complex, including the ore zone. At depth the alteration zones and the ore extend more than a mile east-northeast from the strong fault that lies between the basement rocks on the northeast and the Gila conglomerate on the southwest, and the ore zone dips steeply south. A short distance north of the west central part of the ore body a small zone of intensely argillized rock crops out but its third dimension has not been established by drilling. It is characterized by much potash clay, kaolinite, alunite, and halloysite. To the south and to the west the argillic zone gives way abruptly to a second zone in which pyrite and hydromica are the predominant alteration minerals; this second zone contains about 0.1 percent copper as disseminated chalcopyrite and is the footwall of the ore body. The third zone of alteration, the ore zone, trends east-northeast and is marked by intense sericitization and minor introduced quartz. The primary ore minerals are chiefly disseminated chalcopyrite with some bornite, both associated with abundant early pyrite. A fourth zone, the hanging wall of the ore zone, is much less altered than the rock to the north, but has some chlorite and allophane, and a moderate amount of hydrobiotite in micro-veinlets and as an alteration product of original biotite.

Mid-Tertiary (?) volcanic rocks with an aggregate thickness of more than 3,600 feet are present in the region immediately north and west of the San Manuel district. They consist of basaltic and andesitic flow breccias and agglomerates, interbedded with conglomerate, arkose, and some tuff, and are cut by rhyolite and basalt intrusions. The Gila conglomerate is post-ore and unconformably overlies this volcanic series and also the basement complex. It is a poorly sorted, distinctly stratified, slightly lithified conglomerate of late Tertiary and early Quaternary age. Most of the pebbles in it are an inch or less in length, although cobbles 5 or 6 inches long are abundant and boulders 2 or 3 feet in diameter are not uncommon. The basement complex was the source of most of the debris that accumulated in the lower part of the Gila conglomerate, and cobbles of oxidized ore may be seen in this part of the formation about 40 feet northeast of churn-drill hole 83 (Fig. 2). Higher in the formations are volcanic rocks, including thin beds of tuff; they greatly predominate over other rock types.

Pleistocene and Recent terrace gravels are present chiefly on the sides of the valleys. In the vicinity of the San Manuel deposit the gravels consist largely of reworked Gila conglomerate or waste from the basement complex, reflecting the local source of material. The arroyo bottoms are covered with unconsolidated sandy alluvium, generally to a depth of less than 10 feet.

The quartz monzonite crops out along a structural ridge that trends north-northwest parallel to the Tertiary structure of the region. At San Manuel (Fig. 2) prominent faults separate the quartz monzonite horst from the Gila conglomerate. The ore zone, which trends east-northeast, lies athwart the south end of the quartz monzonite horst and thus most of the ore is concealed under Gila conglomerate in the down-faulted blocks. Both the Gila conglomerate and the earlier volcanic series have a strong regional dip northeast; in the San Manuel area this dip averages approximately 30°.

The primary sulfides are pyrite, chalcopyrite, and minor molybdenite; the primary ore averages about 0.9 percent copper and contains traces of precious metals. In the oxidized zone most of the copper is chrysocolla but some cuprite and native copper are present. An analysis of an average of 23 samples taken on the ore outcrop gave a copper content of 1.1 percent, according to unpublished data in the files of the U. S. Geological Survey. A poorly developed zone of supergene enrichment, containing chalcopyrite with minor amounts of covellite, bornite and native copper, and much residual pyrite and chalcopyrite, underlies the zone of oxidation but does not conform to the present water table.[5] A zone of slight supergene enrichment also is present in the pyrite-hydromica zone of alteration north of the ore body.

SAMPLING.

In order to disclose how the copper was dispersed by weathering and erosion from the ore body, samples of soil, alluvium, ground water, and plants were taken in the vicinity of the ore body. A major problem in sampling was to find a method that would give comparable results for the soil and the alluvium, and clearly show significant variations in heavy metal content. Both the soil and alluvium are mixtures, but in markedly different proportions, of pebbles, sand, and silt. Fifteen samples were taken and separated into fractions representing coarse fragments (2.0 to 0.208 mm, + 80 mesh), coarse fragments ground fine, and fine fragments (less than 0.208 mm). The analyses of these samples are given in Table 1, and show that the copper content of the fine fraction is generally higher than the copper content of the coarse fraction as determined by the field test. A study of the figures given for the coarse fraction when ground fine indicates that the difference between the coarse and the fine fractions results in part from an actual excess of copper in the original fines and in part from incompleteness of extraction of copper from coarse fragments in the sample digestion (Table 1).

The use of fine fractions for sampling has two advantages: it accentuates the copper content, and it avoids grinding. It might be thought that the use of fines would decrease sampling errors by tremendously increasing the number of fragments in the sample. However, a study of sampling error, described in the section on alluvium, indicates only a slight difference in sampling error.

In the routine soil sampling only the fraction less than 80 mesh in diameter was collected. It is believed that the results demonstrate that any sampling and analytical errors inherent in the methods are too small to obscure the significant geochemical variations.

In sampling soil, the pebbles were scraped from the land surface at four spots, usually from the corners of a 4-foot square, and the soil underneath was sieved immediately. Thus each sample is a composite of four grab samples. For each alluvial sample about 16 grab samples were taken from a profile across the alluvial belt and composited when sieved. Both soil and alluvium samples were preserved in Kraft paper envelopes for analysis. Any dampness

[5] Schwartz, G. M., Oxidation and enrichment in the San Manuel copper deposit, Arizona: Econ. Geol., vol. 44, pp. 253–277, 1949.

TABLE 1.

COMPARISON, BY FIELD TEST, OF THE COPPER CONTENT IN THREE FRACTIONS OF FIFTEEN SAMPLES.

Coarse fractions include sizes from 2.0 to 0.208 mm (+80 mesh) in diameter; fine fraction is less than 0.208 mm in diameter.

Field No.	Lab. No.	Description	Size fractions by weight per cent		Copper concentration by field test in parts per million.		
			Coarse	Fine	Coarse	Coarse ground fine	Fine
S1	4928	Soil from quartz monzonite near oxidized ore	70	30	400	400	800
S2	4929	Soil from oxidized ore	67	33	6,000	8,000	12,000
S112	4930	Soil from Gila conglomerate	62	38	30	60	80
S3	4931	Talus	60	40	60	80	120
S151	4932	Soil from barren quartz monzonite	75	25	40	40	60
S61	4933	Soil from Gila conglomerate	71	29	30	40	40
S46	4934	Soil from oxidized ore	69	31	8,000	14,000	13,000
A79	4935	Alluvium from wash just below oxidized ore	89	11	140	200	200
A9	4936	Alluvium 200 feet down the wash from A7	89	11	130	190	150
T84	4937	Terrace at sample site A82	82	18	40	40	30
A7	4938	Alluvium from wash just below S1–S3	81	19	140	500	600
A82	4939	Alluvium about 0.5 mile below ore outcrop	90	10	160	240	240
A92	4940	Alluvium about 1.4 miles below outcrop	86	14	60	120	300
A8	4941	Alluvium about 400 feet down the wash from A7	82	18	270	350	320
OA10	4942	Older alluvium at sample site A9	72	28	600	700	600

in the soil caused the sieve to clog, so sampling was confined to days when the soil was thoroughly dry.

Water samples from churn-drill holes were obtained by lowering a 500 ml pyrex bottle on a wire cable down to the water table. Vegetation samples consisted of leaves and stems plucked from the plant or of cuttings from the fleshy growth, and included a representative portion of any spines present.

FIELD TEST FOR COPPER.

Trace analyses require the use of sensitive analytical methods and are ordinarily made only in a well-equipped laboratory. However, in a study such as the one described here, immediate analytical results are essential in the day-by-day planning of the field work, and the delay attendant on shipping samples to a central laboratory should be avoided. Field tests comparable to the laboratory techniques described by Sandell[6] are being developed currently by the Geochemical Prospecting Section for the determination of traces of metals.[7]

[6] Sandell, E. B., Colorimetric Determination of Traces of Metals, 487 pp., Interscience Publishers, Inc., New York, 1944.

[7] Huff, L. C., A sensitive field test for heavy metals in water: ECON. GEOL., vol. 43, pp. 675–684, 1948.

Reichen, L. E., and Lakin, H. W., Field method for the determination of zinc in plants: U. S. Geol. Survey Circ. 41, 1949.

Lakin, H. W., Stevens, R. E., and Almond, H., Field method for the determination of zinc in soils: ECON. GEOL., vol. 44, pp. 296–306, 1949.

At San Manuel some of the copper of the oxidized ore is in the form of native copper and cuprite but most of it is in the form of chrysocolla. A series of tests for copper was made under the microscope to determine the efficacy of various reagents in digesting chrysocolla, and hydrochloric acid was finally selected for use as a digestant. With hydrochloric acid as a digestant a rapid field method was developed for determining copper in the San Manuel samples; the field test proved satisfactorily accurate and greatly expedited the work.

TABLE 2.

COMPARISON OF LABORATORY* AND FIELD DETERMINATIONS OF COPPER.
Concentrations in parts per million.

Sample No.	Description	Copper by field test	Laboratory analysis		
			Copper	Zinc	Lead
S184	Soil from oxidized ore	280	570	300	90
S172	Soil from oxidized ore	160	320	160	80
S46	Soil from oxidized ore	16,000	9,500	55	55
S75	Soil from diabase dike near oxidized ore	13,000	9,000	110	60
S189	Soil from monzonite porphyry	70	150	100	80
S151	Soil from quartz monzonite	15	30	90	55
S192	Soil from felsite	130	310	90	70
S112	Soil from Gila conglomerate	80	80	150	65
S61	Soil from Gila conglomerate	40	30	130	40
A163	Alluvium immediately downstream from ore outcrop	2,400	3,100	90	60
A82	Alluvium about 0.5 mile below ore outcrop	240	600	120	30
OA83	Older alluvium near sample site A82	180	540	110	40
T84	Terrace alluvium near sample site A82	30	60	110	55
A92	Alluvium about 1.4 miles below ore outcrop	300	530	120	35
OA181	Older alluvium near sample site A92	30	80	180	65
A89	Alluvium from mouth of Mammoth Wash, 3.2 miles below ore outcrop	30	80	100	25
A95	Alluvium from San Pedro River above mouth of Mammoth Wash	40	110	80	20
A96	Alluvium from tributary to San Pedro above A95	15	40	110	20

* Laboratory determinations made by F. Ward, U. S. Geological Survey.

Table 2 presents a comparison of field analyses and analyses by the specific laboratory procedure described by Holmes [8] for a series of representative samples. The results indicate that in most of the samples about half the copper was extracted by the field test, but where more than 0.2 percent copper is present, the field-test values approach the total copper more closely. It is apparent that the dispersion pattern based on the field-test data is esentially the same as that based on laboratory data, although the strength of the pattern differs.

The field test made it possible to analyze samples shortly after they were collected. Some analyses were made in a panel truck at San Manuel (Fig. 3), but most were carried out in a small laboratory at the University of Arizona, in Tucson. A list of equipment needed for making the field test and directions for making the test are given in the appendix.

[8] Holmes, R. S., Determination of total copper, zinc, cobalt, and lead in soils and soil solutions: Soil Science, vol. 50, pp. 77–84, 1945.

DISPERSION OF COPPER IN SOILS.

Although oxidation and supergene alteration have affected most of the rock above the ground-water table, the layer of residual soil is thin (Fig. 4). The soils developed on the rocks of the basement complex have properties determined largely by the type of hydrothermal alteration rather than by the original lithology. Weathering of the argillic zone gives rise to a light-colored, sandy,

FIG. 3. Mobile Laboratory of the U. S. Geological Survey.

kaolinic soil low in heavy metals as shown by analyses of Sample S5 and others nearby. The second or pyrite-hydromica zone weathers to a conspicuous red hematitic soil. The low copper content of the original rock was made still lower by leaching with the sulfuric acid generated by the weathering of pyrite. Soil samples S148 to S153 [9] and others in this zone contain only about 20 parts per million of copper—only about 2 percent of the amount originally present.

The slow present-day weathering of the ore zone [10] is probably accompanied by little movement of copper, but the presence of the tilted and faulted

[9] See Sample Location Key, p. 504, for coordinates of samples, which are shown on Figure 2.

[10] Lovering, T. S., Geothermal gradients, recent climatic changes and rate of sulfide oxidation in the San Manuel district, Arizona: ECON. GEOL., vol. 43, pp. 1–20, 1948.

chalcocite zone shows that at an earlier time a substantial amount of copper moved downward in an acid solution to the ground-water level. The amount of copper removed from the oxidized zone was not a large fraction of the total, however, as the tenor of the oxidized ore is not much less than that of the pri-

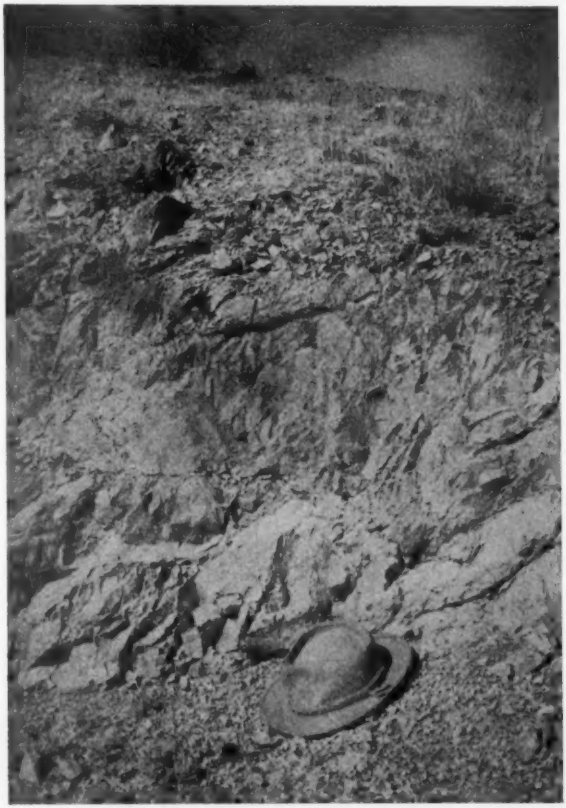


FIG. 4. Shallow cut about 20 feet north of churn drill hole.

mary ore. Some of the soil now forming over the oxidized zone in the present alkaline semiarid environment is as high in copper as the chalcocite zone; this fact stands in marked contrast to the behavior of copper in the second or pyrite-hydromica zone. Gila conglomerate, the dominant bedrock formation of the area, commonly weathers to a thin stony soil armored with residual pebbles and boulders showing little or no evidence of chemical weathering. A mixture of pebbles, sand, and silt lies below the pebble layer and grades at very shallow

depth into the underlying weathered rock. Evidence of chemical weathering is very meager, except for caliche layers and cement, and the copper content is low, as shown by many samples.

SAMPLE LOCATION KEY.

Location of samples not shown on Figure 1, to which reference is made in text. Coordinates are shown on Figure 2.

Alluvium samples:

A 11, 3150 E, 1750 N
A 132, 1070 E, 1155 N
A 134, 630 E, 1470 N
A 136, 450 E, 1580 N

Soil samples:

S 45, 1285 E, 1510 N
S 46, 1320 E, 1530 N
S 48, 1400 E, 1575 N
S 49, 1460 E, 1610 N
S 54, 1930 E, 1880 N
S 70, 1260 E, 1340 N
S 73, 1140 E, 1560 N
S 111, 2500 E, 2000 N
S 148, 150 E, 2810 N
S 153, 275 E, 1970 N
S 169, 1000 E, 1575 N
S 195, 3180 E, 1440 N
S 197, 3130 E, 1590 N

Terrace samples:

T 98, 2500 E, 1800 N

Analyses show that wherever the soil is derived from the immediately underlying rock, as on ridges, the copper content of the soil bears an especially close relation to the copper content of the parent rock. On the outcrop of oxidized ore, where joint surfaces coated with chrysocolla are an obvious indication of high copper content, the samples of soil contain from 1,000 to 10,000 parts per million of copper. Soils on hillsides are contaminated by the soils upslope and must be regarded as a mixture of the indigenous soil with that which has moved down from the hillside above. For example, some soils from the oxidized ore (samples S169, S73, and S45, Fig. 2) containing less than average copper show the effect of dilution by the barren soil from the Gila which has washed down from the ridge to the southwest. In contrast, soils (samples S48 to S54) derived from the Gila show the effect of copper-rich soil creeping down the hillside from the ore outcrop. A high copper content in samples taken at the base of a hillside thus may indicate the presence of copper ore on the hillside above; secondary sample profiles extending upslope from copper-rich samples should locate their source accurately.

In part of the lower arkosic unit of the Gila conglomerate, (samples S195 and S197) the abundant detrital oxidized copper ore derived from the San Manuel deposits, together with minor supergene migrant copper associated with it, gives the soils from the Gila a copper content of several hundred parts per million; but the soils derived from the overlying volcanic debris higher in the formation contain only from 10 to 20 parts per million copper.

FIG. 5. Typical desert wash near sample site A–11.

FIG. 6. View eastward from side of Red Hill showing the head of Mammoth Wash and the San Pedro Valley beyond.

At San Manuel, structural complexities prevent reconstruction of the copper dispersion pattern that developed when the Gila was deposited. In other areas, however, similar "fossil" dispersion patterns may be of some use in prospecting.

DISPERSION OF COPPER IN ALLUVIUM.

The alluvium in desert arroyos that drain the area is a fairly well sorted mixture of coarse sand and fine pebbles. At the head of the washes the area of Recent alluvium is only a few feet across, but as shown in Figures 5 and 6, the alluvial belts coalesce and widen downstream; where the larger washes empty into the San Pedro River, the belt of Recent alluvium is more than one hundred yards wide. There is little change in the size or general character of the alluvium from the head of Mammoth Wash, which drains San Manuel, to its mouth.

The alluvium was sampled at intervals beginning with the small washes immediately below the outcrop of the oxidized ore and extending as far as the mouth of Mammoth Wash where it empties into the San Pedro River. For comparison, other samples of alluvium were taken along the San Pedro River and in other small and large washes in the vicinity of San Manuel. The location of these samples and the copper content of each are shown on Figures 1 and 2; laboratory determinations of zinc and lead also for a representative group of the samples are given in Table 2.

The analyses show that the fine fraction of the alluvium immediately below the oxidized ore has a copper content of 1,000 to 5,000 parts per million (0.1 to 0.5 percent)—only slightly less than that of the soil derived from the oxidized ore. The high copper content clearly indicates proximity to a copper deposit, but analyses of samples at this place would hardly be necessary for prospecting as tiny fragments of chrysocolla are recognized easily in the alluvium. Downstream the concentration of copper decreases until at the mouth of Mammoth Wash, about 3.1 miles below the outcrop of the oxidized ore, it is only 30 parts per million.

Many of the churn-drill holes of the area penetrate rock relatively rich in copper, and drill cuttings, after being washed down the hillside and incorporated in the alluvium, have modified the natural dispersion pattern. The effect is well shown in a small gully just southwest of the main outcrop of oxidized ore. In the basin drained by the gully, the soils derived from the Gila have a copper concentration averaging only 30 parts per million. The alluvium in this wash has a much higher copper content, which reaches an extreme of 1,100 parts per million at sample site A-132. From sample site A-132 the copper content decreases stepwise above churn-drill holes 6, J, and C. Drill cuttings from churn-drill hole C form an easily traceable train extending downhill from the drill hole (Fig. 2); in the alluvium of the gulch below this train, the copper content at A-134 is 220 parts per million but above the train the copper content at A-136 is only 20 parts per million. It is apparent that in the alluvium of this small gulch, the copper content is derived largely from the drill cuttings.

A series of closely spaced samples, T98 to S111, was taken in one of the principal washes to evaluate further the effect of contamination. The Recent

alluvium, which is affected most by contamination, has a copper concentration averaging about 300 parts per million. The older alluvium nearby is a foot or two higher than the Recent alluvium and is covered by well-developed perennial brush, probably predating all drilling. The older alluvium has a copper concentration averaging about 250 parts per million. Standing about 20 feet above the alluvial flat is a terrace of reddish sand and gravel derived, like the alluvium, from erosion of Red Hill and the oxidized ore. When the terrace was formed, however, the area of the ore outcrop was probably less than at present, and some of the copper may have been leached from the gravel after the terrace was formed; certainly it could not have been contaminated by drill cuttings, even those from the earliest holes drilled about 30 years ago. The copper content of the terrace soil now averages about 140 parts per million. Clearly the original natural anomaly at this locality equals or exceeds any increase caused by contamination from drill cuttings in the adjacent recent alluvium.

On the basis of samples from old alluvium or terrace unaffected by contamination, the natural anomaly is traceable to OAl–181 (Fig. 1), which has a copper concentration of 30 parts per million, 1.4 miles below the outcrop of oxidized ore. Thus, the effect of an ore outcrop 70,000 square feet in area within a basin having an area of 42,000,000 square feet—600 times as large—can be detected in the wash 1.4 miles below the outcrop. Below A92 the wash draining the ore body is diluted by several larger washes downstream. The copper content of the alluvium, including the recent possibly contaminated alluvium, is not markedly higher than that of soils and alluvium of blank areas.

Chrysocolla occurs chiefly as joint fillings in the ore outcrop, and, when the rock disintegrates, much of the chrysocolla is preserved as a surface coating, representing the former joint surface, on pebbles and coarse sand grains. The concentration of copper in the fine fraction of the alluvium, as shown by Table 1, reflects the susceptibility of chrysocolla to abrasion. To investigate further the alluvial concentration of copper and to obtain some information concerning sampling error, nine series of cross-channel samples, spaced ten feet apart, were taken east from coordinates 2530 E, 1800 N, Figure 2, for a total of 27 cuts. Laboratory results demonstrated that the fine fraction has a consistently higher copper content than the coarse fraction. The mean of the 27 samples of the coarse fraction is 309 parts per million, and of the fine fraction 367 parts per million, which is 19 percent higher. The average deviation of copper content in the coarse and the fine fractions amounts to 26.9 and 26.4 parts per million, respectively. These figures are about the same, but when expressed as a fraction of the mean they amount to 8.7 and 7.2 percent respectively. In other words the sampling error was somewhat lower for the fine than for the coarse samples.

The concentrations of zinc and lead in the alluvium reveal dispersion patterns entirely different from that of copper. The zinc content in soils derived from the country rock is about 100 parts per million, essentially the same as that in alluvium. The soil of the ore body at San Manuel contains comparatively little zinc and the alluvium below it shows little or no anomaly. Even if the zinc content of the ore were high, it is probable that the zinc contributed by the ore deposit could be traced for only a short distance downstream, because of

the high "background" value. It is apparent that the practicability of tracing metals by alluvial methods depends upon their relative concentration in the ore and in the country rock.

DISPERSION OF COPPER IN GROUND WATER.

One of the principal reasons for making this investigation was to determine whether, during the normal process of weathering and erosion, the ore metals are discharged as stream-transported sediment or as salts dissolved in the ground or surface water. As there was no surface runoff during the period of investigation, no surface waters could be sampled. However, the ground-water body, which has had the greatest opportunity to dissolve the ore metals, can be sampled readily in churn-drill holes. The general eastward slope of the water table indicates an eastward flow of the main ground-water body, and samples were taken in suitable churn-drill holes up drainage and down drainage from the ore body near the outcrop of the oxidized ore. The results of the analyses of these samples are given in Table 3.

TABLE 3.

ANALYSES OF WATER SAMPLES TAKEN FROM CHURN-DRILL HOLES AT SAN MANUEL.

Churn drill hole No.	Depth to water from land surface*	Altitude of water level	Acidity (pH)	Total dissolved solids (parts per million)	Metal content of water (parts per million)			Metal content calculated in terms of dissolved solids (parts per million)		
					Copper	Zinc	Lead	Copper	Zinc	Lead
86	150	2,980	7.7	—	0.02	0.01	<0.01	80	40	<40
73	310	2,755	7.4	250	0.02	0.02	<0.01	80	80	<40
M	636	2,573	7.5	250	0.06	0.06	<0.01	240	240	<40
64	535	2,547	7.5	240	0.08	0.06	<0.01	320	240	<40
63	569	2,554	7.5	260	0.04	0.02	<0.01	160	80	<40
Q	613	2,621	7.6	250	0.02	0.02	<0.01	80	80	<40
L	618	2,698	7.5	280	0.02	0.01	<0.01	80	40	<40

* February, 1948.

The samples from churn-drill holes 86 and 73 represent drainage in the Gila conglomerate perched above the regional water table and are no doubt representative of ground water in nonmineralized terrain. The water level in the other wells sampled ranges from 2,547 to 2,698 feet in altitude or from 535 to 636 feet below the land surface. The ground water in these samples either came directly from the ore deposit or has percolated through the deposit. The analyses of these samples reveal only a very slightly higher copper and zinc content than the samples from the perched ground water. They show no significant contrast in acidity. The results seem to indicate that very little copper was dissolving in the ground water in 1947.

In Table 3 the copper content has been calculated in terms of the total dissolved solids in the water. If an ore mineral has a tendency to dissolve, the proportion of ore metal in the salts in solution should be higher than in the original rock. In the samples from churn-drill holes 86 and 73, representing

drainage from nonmineralized terrain, the analytical results show about 80 parts per million of copper in the dissolved salts, which is of the same order of magnitude as the metal content in average igneous rocks.[11] The highest value obtained in drainage from the ore body, 320 parts per million of dissolved solids, in the sample from churn-drill hole 64, is only four times as high and certainly falls far short of the concentration range observed in the soil and alluvial samples. These results suggest that the ground water is saturated by a very small amount of copper, and that prospecting on the basis of water analysis would not be successful under such conditions. It would be difficult to obtain samples in advance of drilling, and water analyses, even of samples taken within or near the ore body, would not contain concentrations of metal significantly higher than samples taken from barren rock.

PLANT INDICATORS.

Plants growing near ore deposits have been studied [12, 13] both as accumulators and as indicators of the ore metals. An ideal accumulator plant is one that is widely distributed, and contains the characteristic element in proportion to the amount in the soil. The use of accumulator plants to locate concentrations of metal involves the analysis of specimens of the plant from every part of the area being studied. An ideal indicator is one that grows only on soils rich in the ore metal. The use of indicator plants involves merely their identification to locate concentrations of metal.

A number of plants growing over the oxidized ore at San Manuel were analyzed for copper and the results are given in Table 4. The analyses show that the amount of copper accumulated by the plants is very small in comparison with the amount in the soil. Possibly the lack of accumulation is related to the alkalinity of the desert soil and the resulting immobility of the copper; certainly the results contrast sharply with the accumulation of copper by plants noted in humid climates.[13] Whatever the cause, it seems clear that under conditions similar to those at San Manuel, analysis of plants for copper offers no advantages over the direct analysis of the soil.

When the flora of the San Manuel area was studied for possible indicator plants, it was discovered that nearly every species present is affected in some way by its geologic environment. Each of the rock types—the oxidized ore, the Gila conglomerate, and the barren basement series—seems to have its own characteristic plant assemblage. The effect of geology is particularly noticeable along faults where both sides have apparently identical exposure and moisture conditions, yet exhibit marked differences in flora. Table 5 shows the more obvious vegetation contrasts. Dr. Robert A. Darrow, of the University of Arizona, kindly visited the area and identified the plants for the writers. Dr.

[11] Sandell, E. B., and Goldich, S. S., The rarer metallic constituents of some American igneous rocks: Jour. Geology, vol. 51, pp. 99–115, 167–189, 1945.

[12] Robinson, W. O., Lakin, H. W., and Reichen, Laura A., The zinc content of plants of the Friedensville zinc slime ponds in relation to biogeochemical prospecting: ECON. GEOL., vol. 42, pp. 572–582, 1947.

[13] Warren, H. V., and Howatson, C. H., Biogeochemical prospecting for copper and zinc: Geol. Soc. America Bull., vol. 58, pp. 803–820, 1947.

Darrow also identified many small plants, not listed in Table 5, which exhibit the same type of geologic preference.

Of possible interest to prospectors are species like the Rothrock grama grass, the California poppy, and the scrub oak which in this locality grow only on the oxidized ore. Some of these plants can be seen in Figures 7 and 8. The bright orange blossoms of the California poppy accurately and very impressively defined the limits of the oxidized ore at San Manuel in March 1948.

TABLE 4.

COPPER AND ZINC CONTENT OF PLANTS GROWING ON THE OXIDIZED ORE.
Concentration given in parts per million.

Plant	Copper		Zinc in air-dried sample
	in air-dried sample	in ash (inorganic residue)	
Hedgehog cactus (*Echinocereus rectispinus* var. *robustus*)	90	800	35
Shrubby buckwheat (*Eriogonum Wrightii*)	80	800	30
Rothrock grama grass (*Bouteloua rothrockii*)	85	750	45
Staghorn cholla (*Opuntia acanthocarpa*) *	80	750	20
Scrub oak (*Quercus turbinella*)	15	500	20
Saguaro (*Cereus giganteus*) *	60	350	55
Creosote bush (*Larrea tridentata*)	35	350	25
Paloverde (*Cercidium microphyllum*)	30	300	15
Barrel cactus (*Echinocactus wislizeni*) *	25	150	10
Jumping cholla (*Opuntia fulgida*) *	20	100	20
Prickly pear (*Opuntia engelmani*)	20	80	25
California poppy (*Eschscholtzia mexicana*)	75	—	50
Slender grama (*Bouteloua filiformis*)	35	—	40

* Specimens, because of limited distribution, collected from soils containing a high copper content but slightly downhill from the area mapped as oxidized ore in Figure 2.

The greatest concentration was on the ore itself; poppies were present also near samples S48 and S49 where soils derived from the Gila formation are contaminated by surface wash from the oxidized ore; over basal Gila known to be rich in copper near sample sites S-195 and S-197; and in the terrace deposits at sample sites T-182 and T-183 which have a copper concentration well above the average. A casual examination of the Copper Creek district, the Mammoth St. Anthony mine, the Old Hat district, and several others near Tucson, revealed many poppies growing in soils that undoubtedly have a high metal content. Although the poppy distribution may not be directly related to high copper content of the soil they are clearly associated at San Manuel and possibly the association could be utilized for prospecting elsewhere. The ecological factors involved are undoubtedly similar to those discussed by Billings.[14]

[14] Billings, W. D., Vegetation and plant growth as affected by chemically altered rocks in the western Great Basin: Ecology, vol. 31, pp. 62–74, 1950.

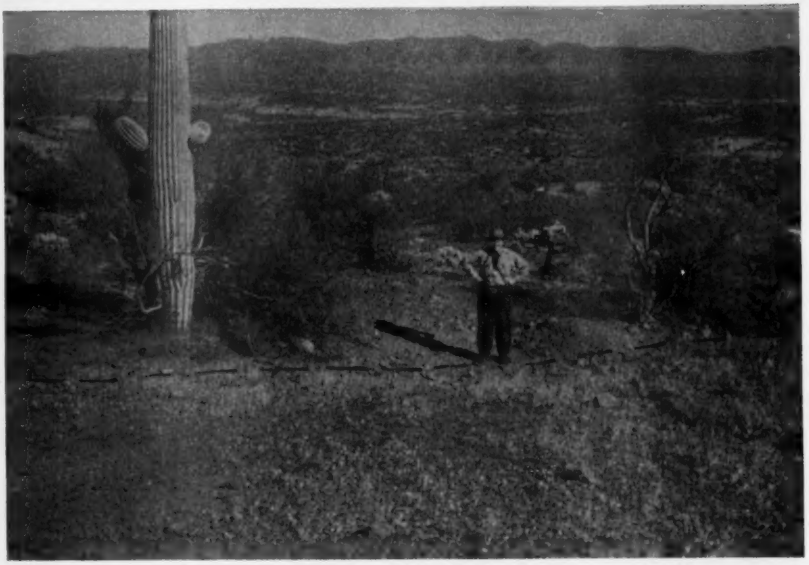


FIG. 7. View northward from sample site S 70. Outcrop of ore body enclosed by dashed lines.

FIG. 8. View northeastward from sample site S 46. Oxidized ore in foreground; barren Gila conglomerate beyond dashed line.

TABLE 5.

ABUNDANCE OF SELECTED PLANT SPECIES IN RELATION TO GEOLOGIC ENVIRONMENT.

Plant description	Abundance		
	Oxidized ore	Barren basement rocks	Gila conglomerate
California poppy (*Eschscholtzia mexicana*)	abundant	absent	absent
Scrub oak (*Quercus turbinella*)	abundant	absent	absent
Rothrock grama grass (*Bouteloua rothrockii*)	abundant	rare	rare
Creosote bush (*Larrea tridentata*)	present	rare	abundant
Mormon tea (*Ephedra nevadensis* var. *aspera*)	present	present	present
Whitethorn (*Acacia constricta*)	present	common	common
Barrel cactus (*Echinocactus wislizeni*)	rare	rare	present
Prickly pear (*Opuntia engelmani*)	rare	rare	common
Hedgehog cactus (*Echinocereus rectispinus* var. *robustus*)	rare	common	present
Saguaro (*Cereus giganteus*)	rare	common	common
Paloverde (*Cercidium microphyllum*)	rare	abundant	common
Ocotillo (*Fouquieria splendens*)	absent	present	common
Staghorn Cholla (*Opuntia acanthocarpa*)	absent	present	present
Desert buckthorn (*Condalia spathulata*)	absent	common	present
Alfileria (*Erodium cicutarium*)	absent	present	abundant
Jumping cholla (*Opuntia fulgida*)	absent	rare	abundant

CONCLUSIONS.

During the weathering and erosion of the San Manuel copper deposit, the chalcopyrite and bornite of the primary ore alter to chrysocolla in the oxidized zone. At some more humid time during the past, a chalcocite enrichment zone formed near the water table. At present very little copper is going into solution; the amount in the ground water is extremely small and little appears to be available for accumulation by plants. At the land surface the chrysocolla is concentrated largely in the soil fines and as a surface coating on angular pebbles. Erosion of the copper is purely mechanical; the copper-rich soil migrates as a thin layer down the hillside until it reaches one of the desert washes. During floods the copper-rich material is incorporated in the alluvium and swept downstream. There is some reason for believing that mechanical abrasion tends slightly to concentrate the copper in the finer sizes downstream; the net change, however, is a decrease in copper content caused by dilution with copper-poor materials from tributary arroyos. The distance that the copper can be traced depends upon the copper concentration in neighboring rock as well as upon the concentration of copper in the oxidized ore and its area of outcrop.

Geochemical studies of copper dispersion in the basement complex, the Gila conglomerate, ground water, and plants, promise little as an aid in prospecting for ore bodies that come to the surface. The most favorable geochemical approach appears to be studies of the copper dispersion in soils and alluvium. Samples of alluvium more than one mile downstream from the outcrop show a

significant copper anomaly. The dispersion can be traced most easily by sampling only the fine fraction, because the copper tends to concentrate in the silt and clay fraction.

A close relationship exists between plant distribution or ecology and local geology. Certain species such as the Rothrock grama grass, scrub oak, and the California poppy are found on the oxidized ore but not in the surrounding area. A study of these and other plant "indicators" may be of value in prospecting, but at present the causes for the preferential distribution are not known.

APPENDIX.

1. *Equipment Needed for Copper Field Test.*

Demineralized water:—Tap water can be used if it is passed through a Model BD-1 Barnstead laboratory demineralizer to remove all traces of heavy metals. The water should be tested frequently to determine the condition of the demineralizer cartridge.

Dithizone (diphenylthiocarbazone):—A stock solution is prepared by dissolving 0.080 grams of C.P. grade dithizone in 500 ml of C.P. grade carbon tetrachloride. To prevent decomposition of the reagent by light and heat, the stock solution should be stored in a pyrex bottle wrapped in dark heavy paper and kept in a cool place. It is fairly stable without the layer of sulfurous acid or hydroxylamine hydrochloride ordinarily used in the laboratory to keep the dithizone in the keto form. For daily use, 50 ml of the stock solution is diluted to 500 ml with C.P. grade carbon tetrachloride, producing a 0.0016 percent (weight/volume) solution for the analyses.

Test tubes:—Heavy, lipless, 25 × 200 mm, pyrex test tubes were used for digesting samples.

Test tube holder:—For the acid digestion of the sample, the test tubes are held in a holder constructed of two disks of sheet steel welded to a central supporting rod. Each plate has eight holes for test tubes; the holes in the bottom plate are small so that the tubes will not slip through, but large enough to permit the ready flow of heat.

Heat:—The test tubes and test tube holder are heated either over a portable gasoline stove or gas burners in the field.

Graduated cylinders:—Glass-stoppered, pyrex, graduated cylinders of 100 ml capacity are used for the determination. The cylinders are cleaned with aqua regia, rinsed four times with metal-free water, and tested with dithizone to assure absence of heavy metals before the determination.

Bottles:—Glass-stoppered pyrex bottles are used to store demineralized water and to transport water samples. The bottles are cleaned in the same manner as the graduated cylinders.

Hydrochloric acid (1.0 N):—Constant-boiling hydrochloric acid is obtained by distilling C.P. hydrochloric acid in an all-pyrex still. At 760 mm mercury barometric pressure there is about 180.2 grams of distillate per mole of hydrochloric acid. Therefore, 180.2 grams of distillate is diluted with metal-free water to one liter to give a one normal solution. C.P. hydrochloric acid is commonly copper-free and can be used without distillation.

Ammonia (1.0 N):—One normal ammonia can be prepared by dissolving 17.03 grams of ammonia gas in metal-free water and diluting to one liter. Metal-free ammonium hydroxide is difficult to purchase because during storage the aqueous solution has a tendency to dissolve traces of the metals from its glass container.

Ammonium citrate (10 percent). Ten percent citrate solution is purified by shaking with dilute dithizone solution.

2. Procedure for the Copper Field Test.

Reflux 10 grams of sample in a pyrex test tube with 20 ml of 1.0 N hydrochloric acid for 30 minutes. To save time, digest eight samples simultaneously. After diluting to 40 ml and reheating to mix thoroughly, transfer a measured portion or aliquot of the digested sample to a glass-stoppered graduated cylinder. Add one ml of ammonium citrate for every 2 ml of aliquot taken and adjust the pH to approximately 3. This is done by adding a drop or two of thymol blue and then 1 N ammonia dropwise until the red solution just begins to turn yellow (pH 2.5–3.0). Add 5 ml of the 0.0016 percent (weight/volume) solution of dithizone in carbon tetrachloride to the cylinder and shake the mixture for 75 seconds.

Shaking the aliquot for 75 seconds at pH 3 brings most of the copper into the carbon tetrachloride phase as copper dithizonate. The color produced in the carbon tetrachloride phase ranges from green through blue green, blue purple, and purple, to pink. The blue-green color forms with 4 micrograms of copper; and the blue-purple, with 5 micrograms of copper. Repeat, varying the size of the aliquot until the blue-green color is observed, and calculate the copper content of the sample. Check by determining the size of the aliquot that produces a color equivalent to 5 micrograms of copper.

The dithizonate formed is calculated as copper although gold, mercury, palladium, and thallium also react with dithizone at pH 3. Part of any bismuth present also will form a dithizonate. Various modifications of the method can be used to make the test more specific; however, the added complexity was considered unessential for field tests in the San Manuel area. Under conditions of the test, only copper is likely to be in solution.

U. S. Geological Survey,
Tucson, Ariz.,
March 20, 1950.

PRODUCTION, CLASSIFICATION, AND UTILIZATION OF WESTERN UNITED STATES COALS.[1]

V. F. PARRY.

ABSTRACT.

This paper reviews and summarizes pertinent technical and economic facts relating to the utilization of western coals, and discusses classification of coal of interest to the chemical engineer. Average chemical analyses of coal produced in 44 mining fields are presented.

INTRODUCTION.

GENERALLY speaking, the western coals are predominantly noncoking and of lower rank than eastern coals. Because of their nonagglomerating properties, they are somewhat easier to handle in burning equipment and are attractive to chemical engineers for processing in continuous plants. The subbituminous coals and lignites, which constitute the bulk of western fuel reserves, are also attractive fuels for chemical engineers because they have a high reactivity that allows rapid rates of reaction with water at relatively low temperatures. Their availability is high because many good fields have been developed, and the mining costs are potentially low since much of the coal is accessible by strip mining.

Despite the favorable conditions for relatively low-cost mining, the demand for western coal has decreased steadily because of severe competition of the higher-value energy sources—oil, gas, and hydro-power—which are in immediate abundance. Over the past 25 years, the demand for energy from mineral fuels in the Western States has increased about 400 percent to reach the present level, equivalent to 650 million barrels of oil, but coal now supplies less than 18 percent of that energy. As the availability of oil and gas decreases, as it must in the future, judging by the production and discovery rates of these fuels, the increased demand for energy will have to be met by coal, oil shale, or imports. Therefore, much interest has been focused on the relatively large reserves of western solid fuels, and proper understanding of their properties, classification, and utilization is becoming more important.

The future outlook for the western coal industry is good because it is indicated that the demand for solid fuel may treble in 25 years. If industrial activity and population continue to increase on the west coast at the present rate, with no significant increase in oil and gas production, the demand for coal in 25 years to substitute for oil and gas may reach 30 million tons annually. Synthetic oil derived from coal or oil shale may also reach the equivalent of 30 million tons of coal. Additional demands for western coal may result if syn-

[1] Presented at the Annual Meeting of the Geological Society of America at El Paso, Tex., Nov. 10, 1949.

thetic oil for eastern markets is manufactured. Despite these optimistic forecasts, the present condition of the western coal industry is not encouraging because current coal production is about 20 percent less than it was during the peak war demand. Nevertheless, it behooves fuel technologists, chemical engineers, and geologists to anticipate the probable large future use of coal and be ready with technical facts to aid coal in seeking new markets.

All ranks of coal from lignite to anthracite occur in the Western States. Over 80 percent of the estimated reserve is low-rank, nearly half being lignite. One-sixth of the reserve is bituminous, but these coals are relatively lower in rank than eastern bituminous coals because of the high oxygen content. It is conservatively estimated that less than 2 percent of the reserve of western coal

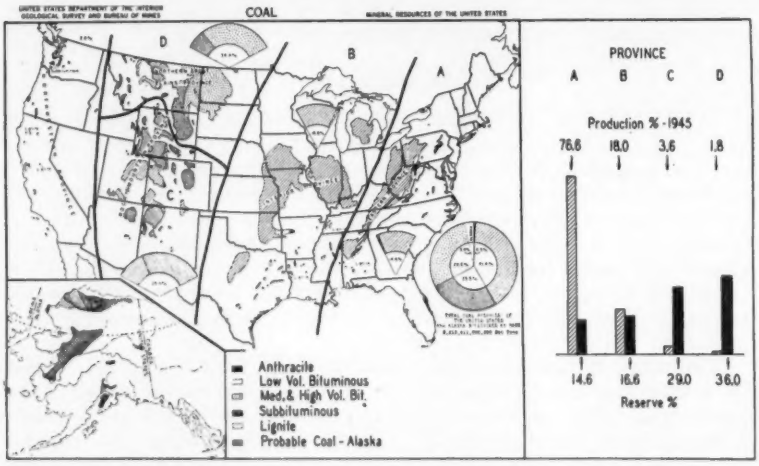


FIG. 1. Distribution of coal resources of the United States and Alaska as of 1944 by types of coal and by provinces. Distribution of production and reserves by provinces—1945.

has coking properties suitable for commercial use. This is an advantage in some ways, because chemical engineers have discovered that the noncoking coals can be processed easier than coking coals. Because of the great variation in rank and quality of western coals, the problem of classification is important, particularly from the viewpoint of chemical engineers.

This paper presents a scheme of classification that appears to have some advantages over the older methods, particularly for utilization purposes. Instead of giving the coals names and dividing them into classes, some of which overlap, causing confusion, the various coals are represented by numbers expressing the heating value of the coal substance. This appears to be a good criterion of rank. A number thus places the coal in the scale of rank and differentiates coals within classes as well as indicating the chemical analysis by reference to a correlating graph. It is shown that average coal advances in

rank in a continuous straight-line relationship with heating value. This is especially true of the lower-rank coals up to high-volatile bituminous A. Above this rank, the coals are distinguished by volatile-matter changes and coking properties. The classification of the great bulk of western coals is simpler when the heating value of the coal substance is employed to express the rank, and this method allows more accurate description of the small differences between coals.

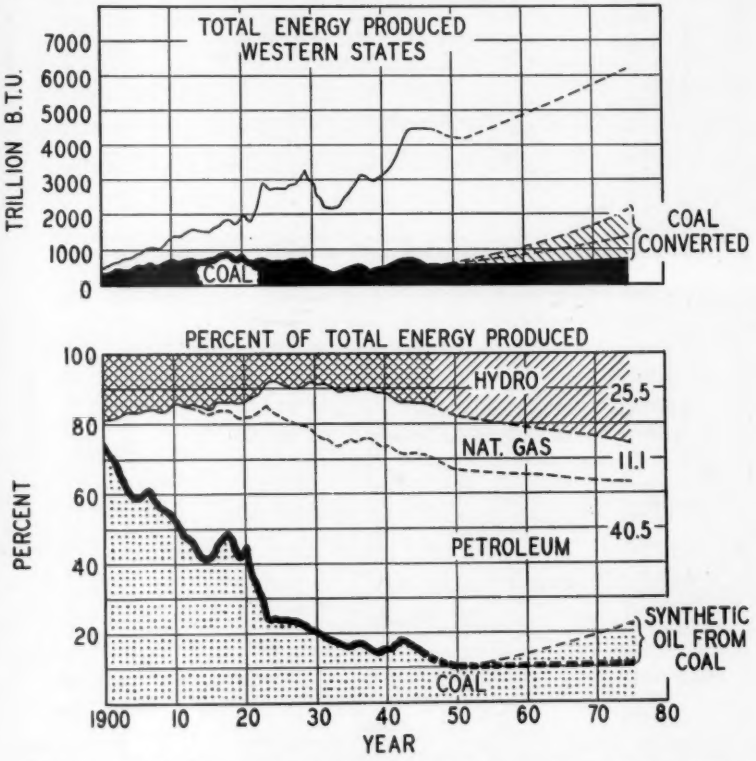


FIG. 2. Trends of energy production in eleven Western States, 1900 to 1975.

SUPPLY AND TREND OF DEMAND FOR WESTERN UNITED STATES COALS.

A coal map of the United States is shown in Figure 1, which gives the coal areas by provinces and data on reserves and production. This paper considers only the coal areas in the Rocky Mountain and Northern Great Plains Provinces. The distribution of reserves is indicated by the black bar chart on the right of Figure 1 and shows that approximately 55 percent of the estimated

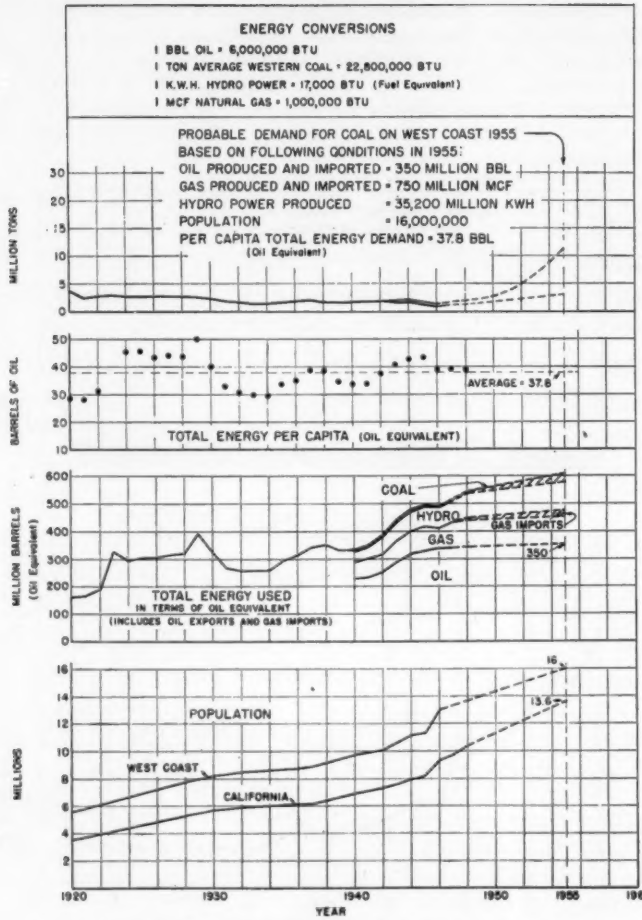


FIG. 3. Trends in energy consumption—West Coast States.

reserve of coal is in the western provinces. The production of coal in 1945 in the different provinces is indicated by the cross-hatched bars. It is significant to note that only 5.4 percent of the national production came from the Western States, and only 1.8 percent was produced in the Northern Great Plains Province, where 36 percent of the reserve is located.

The total energy produced in the Western States, distributed as to types of energy, is illustrated in Figure 2. This graph also indicates a probable trend of production of the different forms of energy during the next 25 years based

on trends of population growth, industrial development, and so forth.[2] This study postulates that, if the supply of oil and gas remains constant and hydropower reaches its planned development, the balance of energy needed may come from coal and coal products. It is indicated that, if the additional energy required is derived from coal, by 1975 the equivalent of 2,100 trillion B.t.u. of coal must be produced. This is equal to approximately 93,000,000 tons—ap-

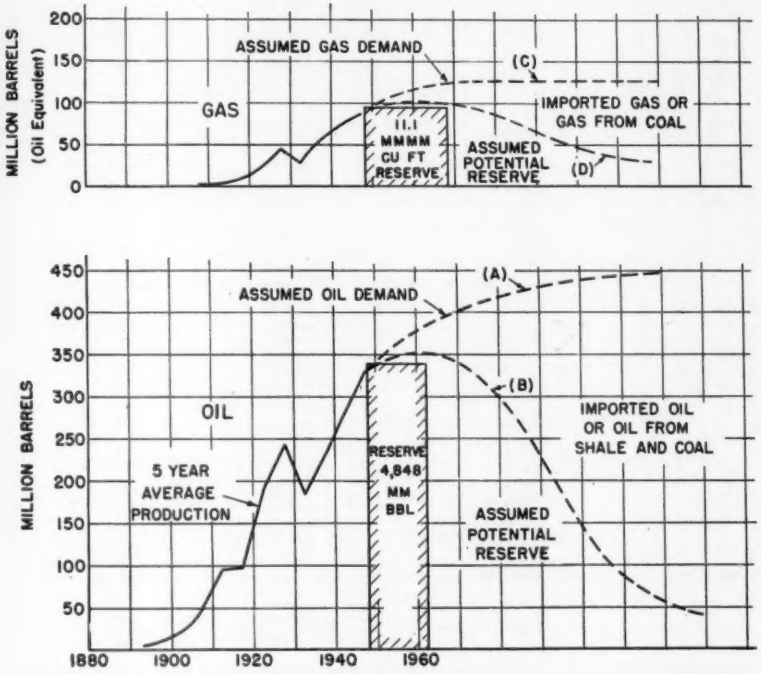


FIG. 4. Oil and gas supply and demand—West Coast States— Oregon, Washington, California.

proximately 3½ times the present production. If oil shale is processed to make fuel oils, the energy thus produced would reduce the demand for coal.

The history of energy production on the West Coast since 1920 with a distribution of the forms of energy produced since 1940 is shown in Figure 3. The graph also shows a correlation of factors affecting increased demand for energy. It is postulated that, if population increases to 16 million by 1955 and the average per capita demand for energy continues at the rate of 37.8 barrels per year, the demand for total energy will be equivalent to approximately 610

[2] Parry, V. F., Trends in the production of coal and energy in the Western States as a result of the war: Rocky Mtn. Coal Mining Inst. Proc., pp. 10–18, May, 1947.

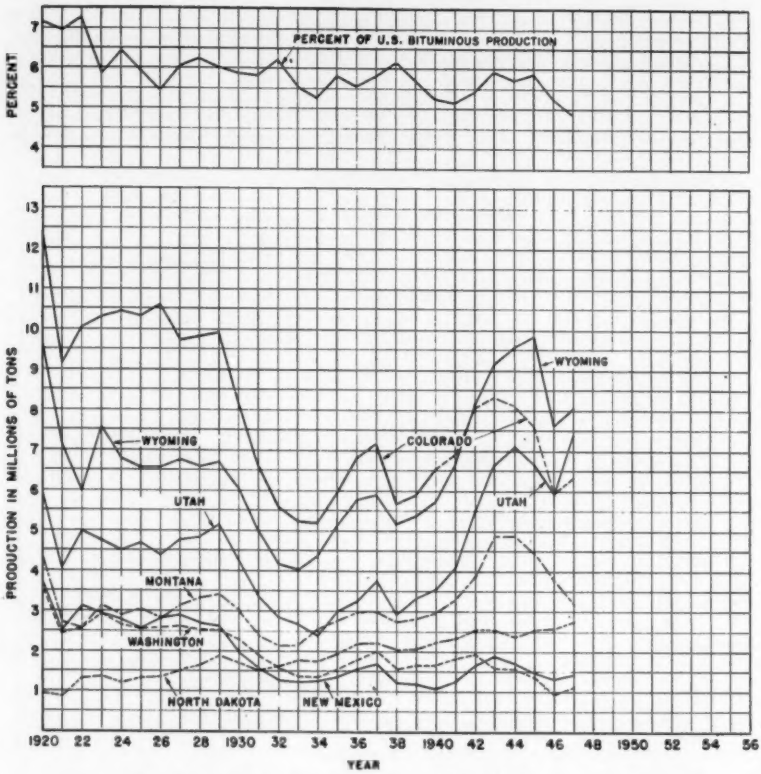


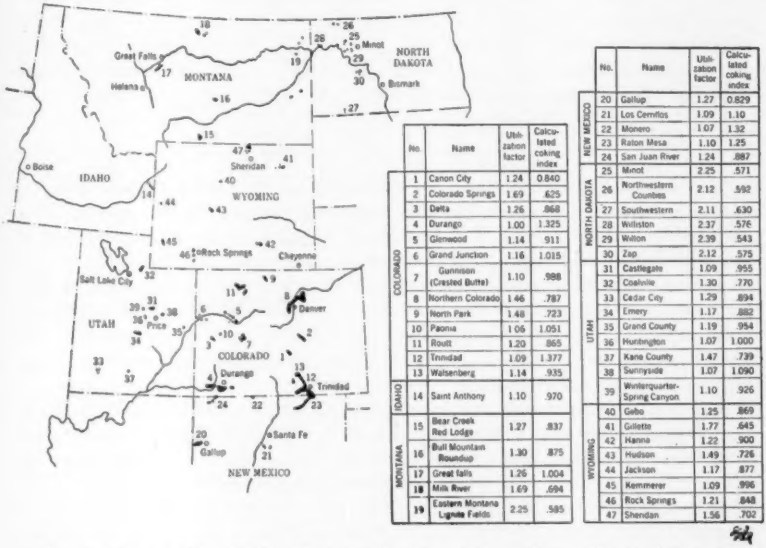
FIG. 5. Production of coal in eleven Western States.

million barrels of oil. Furthermore, if oil and gas production continues at the current high rate and hydropower development and gas imports expand in accordance with present plans, there is an indicated deficit in total energy which probably will have to be met by coal. Coal will probably be in demand for generation of electric power on the West Coast, particularly California, and the additional demand by 1955 may reach 6 to 7 million tons. However, if new oil imports or substantial new oil discoveries are made, the demand for coal will be reduced correspondingly.

A brief description of oil and gas supply and demand in the West Coast States is illustrated in Figure 4 which traces the history of production and shows the present proved reserves. It is evident that the demand for oil and gas will not decrease, and reserves cannot continue to keep up with demand indefinitely. The rate of decline of oil and gas production may be along the dotted lines (B) and (D). The difference between supply and demand is illustrated between

lines (A) and (B), and (C) and (D). Imported oil, shale oil, or products from coal will have to make up this difference.

The actual production of coal in the Western States since 1920 is illustrated in Figure 5. This graph also shows that coal production in the West has decreased since 1920 from 7 to about 5 percent of the national bituminous production—a relative decrease of close to 30 percent. The reason for this is that oil and gas production is relatively higher in the West than in the East. Hence, a change in the oil and gas situation should have a considerable effect on coal production in the West.



	No.	Name	Utilization factor	Calculated coking index
COLORADO	1	Canon City	1.24	0.840
	2	Colorado Springs	1.69	.625
	3	Delta	1.26	.868
	4	Durango	1.00	1.325
	5	Glenwood	1.14	.911
	6	Grand Junction	1.16	1.015
	7	Gunnison (Crested Butte)	1.10	.988
	8	Northern Colorado	1.46	.787
	9	North Park	1.48	.723
	10	Paonia	1.06	1.051
	11	Routt	1.20	.865
	12	Trinidad	1.09	1.377
	13	Walsenburg	1.14	.935
IDAHO	14	Saint Anthony	1.10	.970
MONTANA	15	Bear Creek Red Lodge	1.27	.837
	16	Bull Mountain Roundup	1.30	.875
	17	Great falls	1.26	1.004
	18	Milk River	1.69	.694
	19	Eastern Montana Lignite Fields	2.25	.585
NEW MEXICO	20	Gallup	1.27	0.829
	21	Los Cerrillos	1.09	1.10
	22	Monero	1.07	1.32
	23	Raton Mesa	1.10	1.25
	24	San Juan River	1.24	.887
NORTH DAKOTA	25	Minot	2.25	.571
	26	Northwestern Counties	2.12	.592
	27	Southwestern	2.11	.630
	28	Williston	2.37	.576
	29	Wilton	2.39	.543
	30	Zap	2.12	.575
UTAH	31	Castlegate	1.09	.955
	32	Coalville	1.30	.770
	33	Cedar City	1.29	.894
	34	Emery	1.17	.882
	35	Grand County	1.19	.954
	36	Huntington	1.07	1.000
	37	Kane County	1.47	.739
	38	Sunnyside	1.07	1.090
	39	Wintergquarter-Spring Canyon	1.10	.926
WYOMING	40	Gebo	1.25	.869
	41	Gillette	1.77	.645
	42	Hanna	1.22	.900
	43	Hudson	1.49	.726
	44	Jackson	1.17	.877
	45	Kemmerer	1.09	.996
	46	Rock Springs	1.21	.848
	47	Sheridan	1.56	.702

FIG. 6. Coal mining fields of the Rocky Mountain region, utilization factors.

Coal is produced in approximately 47 different mining fields in the Western States, as illustrated by Figure 6. This figure also includes tabulated average data on the properties of coal in the different fields. The utilization factor indicates the number of tons of coal required to produce the same available heat as can be produced from a ton of average U. S. bituminous coal of 13,600 B.t.u. per pound. For example, 1.24 tons of average coal produced in the Canon City field of Colorado will be required to produce the same amount of steam or synthetic liquid fuel as 1.0 ton of average coal from the Durango, Colorado, field. These utilization factors are calculated from the ultimate analysis and heating value of the average coal from each field by assuming that the coal is burned with 30 percent excess air and the products of combustion leave the system at 500° F. The available heat, indicated by the reciprocal of the utilization factor, is the net heat available for work. The calculated coking index is an arbitrary

scale, figured from the analysis of the coal, which indicates the coking or agglomerating property. A coal having an index greater than 1.0 has agglomerating properties, while an index greater than 1.07 indicates the coal can probably be used in byproduct coke ovens.[3] The relatively great variation in properties of western coals is indicated by the utilization factor and coking index.

ANALYSIS OF ROCKY MOUNTAIN COALS.

The average analysis of coals produced in 44 mining areas of the West is given in Table 1. These analyses are the average from the data on 3 to 6 mines in each field, but in a few instances only one mine was operating. The classification by rank is indicated, and the analysis is reported on the as-received and on the moisture- and ash-free basis (MAF). The field number corresponds to the numbers shown in Figure 6.

CLASSIFICATION OF COAL.

The A.S.T.M. specifications for classification of coal by rank divides the lower-rank coals into seven groups, according to their moist- and mineral-matter-free heating value. The boundaries of some classes are determined by physical properties, such as agglomeration, slacking or weathering, and consolidation. In this scheme of classification, there exist six divisions or borderlines, and coals near these borderlines may be classed higher or lower depending upon measurements which may have considerable error or deviation. This leads to considerable confusion in naming the lower-rank coals, and the classification is not precise enough for chemical engineers.

Chemical engineers are concerned with energy, ultimate analysis, and practical physical properties. Their problem is the handling of solids, energy, and reactions, and their principal aim is to achieve uniformity. Differences between coals become more important than arbitrary limits of values. They must be able to express the quality of coal they are handling in terse and precise figures. They cannot be troubled with controversial definitions. Chemical engineers prefer to think of coal or to classify coal in terms of numbers expressing the important and practical problems of coal handling and utilization. They are interested in heating value, moisture, ash, sulfur content, fixed carbon, coking properties, and physical constituents. The physical properties as to slacking and consolidation are less important to them because in most instances they will deal with pulverized coal for chemical utilization. They are mainly interested in heat and reactions at fairly high temperatures. Therefore, a scheme of classification giving the major properties in terms of numbers will be the most satisfactory.

As coal metamorphoses from lignite to high-volatile bituminous A, it undergoes a steady progression in change of heating value and chemical properties. There are no sharp borderlines for average coal between lignite and bituminous ranks. The most important chemical change in coal substance as it advances

[3] Parry V. F., Trends in the use of energy in the Western States with particular reference to coal: U. S. Bur. Mines Rept. Inv. 3680, 44 pp., 1943.

TABLE 1.

AVERAGE ANALYSES OF COALS OF THE ROCKY MOUNTAIN AND NORTHERN GREAT PLAINS PROVINCES BY FIELDS.[1]

Field no. and rank	Condition[2]	Analysis, percent										B.t.u. per pound	Ash softening temp. °F.
		Proximate				Avg. ash[4]	Ultimate						
		Moisture	Volatile matter	Fixed carbon	Ash[3]		H_2	C	N_2	O_2	S		
Colorado coals.													
1. Canon City	A	10.3	35.2	47.0	7.3	9.4	5.6	64.3	1.1	21.1	0.5	11305	
Bituminous C	B		42.9	57.1			5.3	78.2	1.3	14.6	.6	13740	2300
2. Colorado Springs	A	24.4	32.1	37.5	6.0	7.1	6.4	51.7	0.7	36.9	0.2	8625	
Subbituminous C	B		46.1	53.9			5.1	72.9	1.0	20.6	.4	12400	2300
3. Delta County	A	13.0	35.1	45.8	6.1	7.0	5.9	63.3	1.4	22.5	0.7	11190	
Bituminous C	B		43.3	56.7			5.5	78.5	1.7	13.5	.9	13840	2680
4. Durango	A	3.1	38.1	53.9	4.9	6.3	5.7	77.0	1.6	9.6	1.3	13845	
Bituminous A	B		41.5	58.5			5.8	83.6	1.7	7.5	1.4	15038	2596
5. Glenwood	A	5.0	37.7	51.2	6.1	7.1	5.5	71.4	1.6	14.5	0.7	12720	
Bituminous B	B		42.4	57.6			5.6	80.4	1.9	11.4	.8	14290	2360
6. Grand Junction	A	8.8	35.4	48.9	7.0	10.1	5.7	68.0	1.6	16.9	0.8	12080	
Bituminous B and C	B		42.0	58.0			5.6	80.8	1.9	10.8	1.0	14330	2650
7. Gunnison	A	7.2	36.4	50.3	4.4	5.2	5.9	71.1	1.6	16.7	0.5	12633	
Bituminous B and C	B		43.1	56.9			5.7	80.3	1.8	11.7	.5	14277	2385
8. Northern Colorado	A	22.1	29.8	44.0	4.1	4.6	6.2	56.8	1.2	31.3	0.4	9788	
Subbituminous B	B		40.4	59.6			5.1	77.2	1.6	15.7	.5	13265	2222
9. North Park	A	18.1	32.3	41.3	8.4	8.4	6.0	55.2	1.0	29.0	0.4	9650	
Subbituminous B	B		44.0	56.0			5.4	74.9	1.5	17.7	.5	13040	2490

[1] Analysis of tipple samples from 3 to 6 mines: Lowest ash sample of 3 to 5 sizes sampled from each mine. (Bureau of Mines)
[2] Condition A, as-received basis; condition B, moisture- and ash-free basis.
[3] Ash percentage of lowest ash samples from each mine.
[4] Average ash percentage of all sizes produced.

TABLE 1—*Continued.*

Field no. and rank	Condition[2]	Analysis, percent										B.t.u. per pound	Ash softening temp. °F.
		Proximate				Avg. ash[4]	Ultimate						
		Moisture	Volatile matter	Fixed carbon	Ash[3]		H_2	C	N_2	O_2	S		
Colorado coals—*Continued.*													
10. Paonia	A	5.3	38.9	50.8	4.9	6.2	5.8	73.3	1.5	14.0	0.5	13080	
Bituminous B	B		43.4	56.6			5.8	81.6	1.7	10.4	.5	14565	2487
11. Routt County	A	9.7	37.3	47.4	5.6	6.3	5.7	66.6	1.5	20.1	0.5	11780	
Bituminous C	B		44.0	56.0			5.5	78.5	1.8	13.6	.6	13896	2595
12. Trinidad	A	2.0	32.3	51.5	14.2	16.0	5.0	71.0	1.4	7.9	0.6	12650	
Bituminous A	B		38.6	61.4			5.7	84.7	1.6	7.3	.8	15085	2710
13. Walsenburg	A	5.7	37.4	48.9	8.0	10.1	5.4	69.1	1.3	15.7	0.6	12190	
Bituminous B	B		43.4	56.6			5.5	80.0	1.5	12.3	.7	14105	2395
Montana coals.													
14. Bear Creek—Red Lodge	A	9.9	35.1	47.7	7.3	10.4	5.6	62.8	1.6	20.9	1.8	11073	
Bituminous C Subbituminous A if weathering	B		42.4	57.6			5.5	75.9	1.9	14.5	2.2	13380	2067
15. Bull Mountain—Roundup	A	14.2	31.6	48.1	6.1	7.4	5.8	62.9	1.1	23.7	0.4	10870	
Bituminous C Subbituminous A if weathering	B		39.6	60.4			5.3	78.9	1.3	13.9	.6	13580	2450
16. Great Falls	A	6.8	28.7	48.2	16.3	19.4	4.6	60.4	0.8	14.8	3.3	10687	
Bituminous C	B		37.3	62.7			4.9	78.4	1.0	11.4	4.3	13718	2910+
17. Milk River	A	20.9	28.9	38.3	11.9	12.2	5.7	50.0	1.1	30.8	0.5	8510	
Subbituminous B & C	B		43.1	56.9			5.0	74.4	1.7	18.3	.7	12660	2240
18. Eastern Montana	A	38.6	25.3	30.3	5.8	8.3	7.0	40.5	0.7	45.5	0.6	6725	
Lignite	B		45.4	54.6			4.9	72.9	1.3	20.2	.8	12090	2380

TABLE 1—*Continued.*

TABLE 1—*Continued.*

Field no. and rank	Condition[2]	Analysis, percent										B.t.u. per pound	Ash softening temp. °F.
		Proximate				Avg. ash[4]	Ultimate						
		Moisture	Volatile matter	Fixed carbon	Ash[3]		H_2	C	N_2	O_2	S		
New Mexico coals.													
19. Gallup—Bituminous	A	12.0	37.2	41.7	9.1	11.8	5.9	62.6	1.1	20.8	0.6	11140	
C & Subbituminous A	B		47.2	52.8			5.8	79.3	1.4	12.8	.8	14110	2615
20. Los Cerrillos	A	3.1	35.8	51.4	9.7	9.7	5.2	71.8	1.2	11.2	0.9	12750	
Bituminous A	B		41.0	59.0			5.6	82.2	1.3	9.9	1.0	14610	2320
21. Monero	A	3.0	37.3	49.8	10.0	11.6	5.3	71.5	1.5	9.1	1.6	12970	
Bituminous A	B		42.8	57.2			5.7	82.1	1.8	7.4	3.0	14900	2380
22. Raton Mesa	A	2.4	35.8	48.7	13.1	15.4	5.3	70.6	1.3	9.1	0.7	12652	
Bituminous A	B		42.3	57.7			5.9	83.5	1.5	8.2	.8	14970	2910+
23. San Juan River	A	10.8	38.3	41.9	9.1	10.1	5.9	63.6	1.3	19.4	0.7	11352	
Bituminous C	B		47.7	52.3			5.7	79.2	1.6	12.5	.9	14138	2626
North Dakota lignites.													
24. Minot	A	38.8	25.9	30.5	4.8	7.3	7.0	40.5	0.6	46.8	0.3	6783	
Lignite	B		45.9	54.1			4.8	71.8	1.1	21.8	0.4	12030	2360
25. North Western	A	35.8	26.2	32.2	5.8	9.5	6.9	42.0	0.6	44.3	0.4	7230	
Lignite	B		44.9	55.1			5.0	72.4	1.1	21.0	.7	12353	2137
26. South Western	A	34.8	27.4	30.4	7.4	8.5	6.8	42.7	0.5	41.5	1.1	7330	
Lignite[5]	B		47.5	52.5			5.8	73.9	.9	18.4	1.8	12690	2310
27. Williston	A	42.8	24.9	27.2	5.1	6.3	7.5	37.4	0.6	49.0	0.5	6378	
Lignite	B		47.9	52.1			5.2	71.8	1.2	20.9	1.0	12243	2268
28. Wilton	A	41.7	26.4	27.2	4.7	5.7	7.3	38.4	0.5	48.5	0.6	6510	
Lignite[5]	B		49.3	50.7			5.0	71.5	.9	21.4	1.2	12140	2440
29. Zap	A	36.5	27.3	30.6	5.6	6.9	6.9	41.7	0.6	44.5	0.6	7022	
Lignite	B		47.1	52.9			4.9	72.2	1.0	20.9	1.1	12152	2473

[5] Analysis from 1 mine only.

TABLE 1—*Continued.*

Field no. and rank	Condition[2]	Analysis, percent										B.t.u. per pound	Ash softening temp. °F.
		Proximate				Avg. ash[4]	Ultimate						
		Moisture	Volatile matter	Fixed carbon	Ash[3]		H_2	C	N_2	O_2	S		
Utah coals.													
30. Castlegate	A	6.1	41.3	47.8	4.8	5.8	5.8	71.5	1.4	15.8	0.6	12782	
Bituminous A & B	B		46.3	53.7			5.9	80.3	1.5	11.7	.6	14383	2290
31. Coalville	A	13.7	37.7	44.1	4.5	5.2	6.0	62.2	1.2	25.1	1.1	10950	
Bituminous C	B		46.1	53.9			5.4	76.2	1.5	15.6	1.4	13405	2360
32. Emery County	A	5.0	43.2	46.3	5.6	7.7	6.0	72.5	1.5	13.9	0.5	13115	
Bituminous A & B	B		48.3	51.7			6.1	81.1	1.6	10.7	.6	14663	2178
33. Grand County	A	7.6	36.9	47.3	8.2	8.2	5.6	67.5	1.5	16.6	0.6	12040	
Bituminous B[5]	B		43.9	56.1			5.6	80.1	1.7	11.9	.7	14300	2420
34. Colob-Kanab	A	10.3	39.9	41.8	8.0	9.2	5.6	60.8	1.1	18.6	5.9	10985	
Bituminous C	B		48.9	51.7			5.4	74.6	1.3	11.6	7.2	13455	2170
35. Sunnyside	A	5.1	37.8	50.8	6.1	6.7	5.6	72.3	1.5	13.5	0.9	12954	
Bituminous A & B	B		42.8	57.2			5.7	81.5	1.7	10.1	1.0	14592	2582
36. Winterquarter	A	6.7	42.9	45.5	4.9	5.8	6.0	70.2	1.5	16.9	0.5	12575	
Bituminous B	B		48.6	51.4			6.0	79.5	1.7	12.4	.6	14232	2310

TABLE 1—*Continued.*

Field no. and rank	Condition[2]	Analysis, percent										B.t.u. per pound	Ash softening temp. °F.
		Proximate				Avg. ash[4]	Ultimate						
		Moisture	Volatile matter	Fixed carbon	Ash[3]		H_2	C	N_2	O_2	S		
Wyoming coals.													
37. Gebo	A	13.8	34.9	47.7	3.6	4.4	6.1	64.3	1.4	24.0	0.6	11310	
Bituminous C if weathering Subbituminous A	B		42.2	57.8			5.6	77.9	1.7	14.1	.7	13490	2200
38. Gillette	A	29.1	31.7	32.3	6.9	8.4	6.8	47.0	0.6	37.8	0.9	8280	
Subbituminous C[5]	B		49.5	50.5			5.6	73.4	1.0	18.6	1.4	12930	2230
39. Hanna	A	9.6	38.9	45.6	5.8	6.9	5.9	64.9	1.1	21.8	0.5	11500	
Bituminous C	B		46.0	54.0			5.7	76.7	1.3	15.7	.6	13600	2360
40. Hudson	A	21.7	34.3	39.4	4.7	6.2	6.4	54.9	1.2	32.3	0.5	9603	
Subbituminous B	B		46.6	53.4			5.3	75.7	1.6	16.7	.7	13040	2270
41. Jackson Hole	A	9.9	41.1	45.5	3.5	4.5	6.1	68.4	1.7	19.8	0.5	12060	
Bituminous C[5]	B		47.4	52.6			5.7	79.0	1.9	12.8	.6	13920	2100
42. Kemmerer	A	4.9	39.6	50.2	5.2	8.6	5.6	72.8	1.3	14.3	0.8	12880	
Bituminous A & B	B		44.1	55.9			5.7	80.9	1.5	11.1	.9	14330	2193
43. Rock Springs	A	12.0	37.3	47.0	3.7	4.8	6.0	65.9	1.4	22.2	0.8	11600	
Bituminous B & C	B		44.1	55.9			5.5	78.1	1.7	13.9	.9	13770	2520
44. Sheridan	A	23.8	33.0	38.7	4.5	5.0	6.6	53.4	1.2	33.8	0.5	9298	
Subbituminous B	B		46.0	54.0			5.5	74.5	1.7	17.5	.6	12954	2314

in rank is the decrease of oxygen. The carbon:hydrogen ratio in coal changes only slightly as the rank advances. It is significant that there are no sharp breaks in chemical composition as coal progresses from lignite through bituminous, and the analysis of average coal substance changes in straight-line relationship as the heating value increases. Figure 7 shows the relationship between the ultimate analysis of average coal and the heating value on the moisture- and ash-free basis. The points on this graph are averages of 10 to 20 analyses within the range of 100 B.t.u. in heating value, and the total number of analyses considered was 800 to 1,000. The lines shown designate the analysis of average coal with respect to heating value.

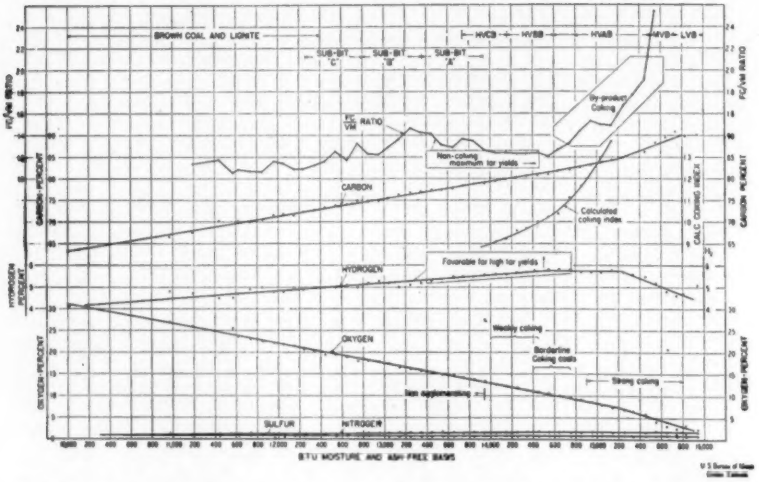


FIG. 7. Classification of average western U. S. coals with respect to fuel ratio, heating value, and ultimate analysis on moisture and ash-free basis.

In the practical use of this diagram, a coal of a given heating value may have a somewhat different chemical analysis than the average. The deviation from the average is important, and chemical engineers or petrographers should be able to interpret the difference from the average. The accounting for the difference may be the key to important utilization factors.

A direct relationship may exist between the difference of hydrogen content of a specific coal from the average and the percentage of attrital matter in the coal. Likewise the difference between the FC:VM ratio of a specific coal from the average may explain petrographic differences. If the analysis of a coal differs considerably from the average, it should be enlightening to make special petrographic and possibly other examinations of such coals.

An examination of the analyses of about 1,000 coal samples used in construction of Figure 7 revealed that the maximum deviation of carbon content from the average was 2.5 percent, hydrogen was 0.6 percent, and oxygen 2.5

percent. In a preview of this paper by Dr. Gilbert Cady, Illinois State Geological Survey, several coals were selected at random for comparison of their analyses with the average determined from the graph. The following table shows this comparison:

Coal	B.t.u. Moisture and ash-free	Analysis					
		Determined			From Figure 6		
		O	H	C	O	H	C
Crested Butte, Colo.	14,200	11.5	5.6	80.7	12	5.6	80+
Sahara No. 16, Ill.	14,700	8.6	5.5	82.9	9	5.7	82.5
Sahara No. 4–No. 5, Ill.	14,700	8.3	5.5	82.2	9	5.7	82.5
Orient No. 1, Ill.	14,600	9.7	5.6	81.9	10	5.7	82.
Majestic, Ill.	14,300	11.2	6.0	79.4	11.5	5.6	80.1
Zeigler, Ill.	14,500	10.2	5.7	81.1	10.1	5.7	81.2
Amherst (Eagle), W.Va.	15,400	5.5	5.6	86.5	6.0	5.5	86.5
Wheelright (Elkhorn), Ky.	15,000	7.0	5.7	84.7	8.0	5.7	83.5
Wheelright, Ky.	15,100	6.9	5.7	85.0	7.5	5.7	84.0
Pocahontas (Carswell), W.Va.	15,800	2.3	4.7	90.9	2.5	4.7	90.0
Eccles (Beckley), W.Va.	15,700	2.0	4.9	90.6	3.5	4.8	89.0

Knowing the heating value of a coal on the moisture- and ash-free basis, chemical engineers can quickly estimate the probable chemical analysis without actually making the analysis. It is indicated that no relationship exists between heating value and the fixed carbon or the fixed carbon:volatile matter ratio as coal advances in rank to high-volatile bituminous A. Beyond this rank, the fixed carbon is an important factor in the criteria of rank. It is further shown by the graph that coals having more than 10 percent oxygen in the coal substance or having less than 14,600 B.t.u. per pound on the MAF basis can be considered as lower-rank.

The A.S.T.M. specifications for classification place great weight on moisture content. Figure 8 shows the relationship between average bed moisture and heating value. In this case, the variation in moisture, as the heating value increases, is considerably greater than the variation in chemical analysis. Moisture is difficult to determine, especially in the lower-rank coals, and care should be exercised in placing emphasis on moisture when classifying coal for chemical engineers. In most instances, for large-scale uses, the lower-rank coals will be dried before use.

For designating the classification and analysis of coal, particularly for chemical engineers, the following is suggested:

$$(138 - 57)\ \mathrm{M12} - \mathrm{A6} - \mathrm{S1.6} - \mathrm{F24}.$$

The first number in the parentheses represents heating value of the coal on the moisture- and ash-free basis expressed in 100 B.t.u.

The second number in the parentheses represents the fixed carbon on the moisture- and ash-free basis, reported to the nearest whole percent.

The numbers and symbols following the parentheses show:

M = total moisture, as received, expressed to nearest percent.
A = ash as received expressed to nearest percent.
S = sulfur as received expressed to nearest $\frac{1}{10}$ percent.
F = ash-softening temperature expressed to nearest 100° F.

By reference to the graph correlating the heating value of average coal with chemical analysis and showing the nearest A.S.T.M. classification by rank, the probable chemical analysis of the coal and the A.S.T.M. rank can be estimated.

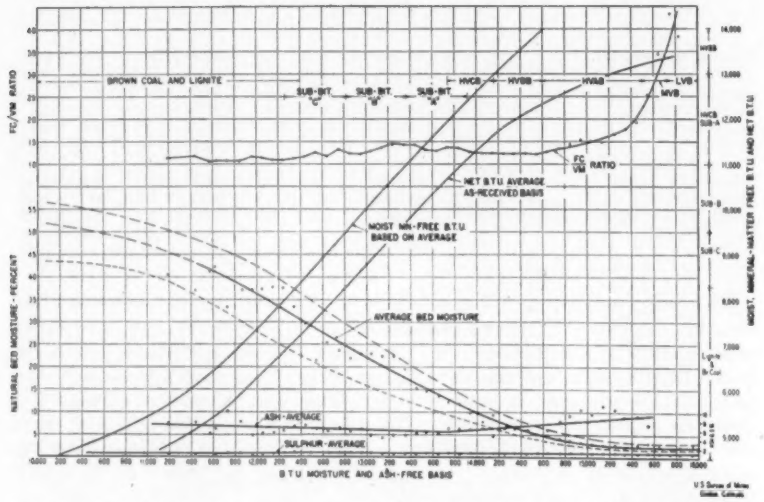


FIG. 8. Classification of average western U. S. coals with respect to heating value, average bed moisture, ash, sulfur, and fuel-ratio.

Figure 9 is another illustration of the western coal fields, with data on the heating value of average coal produced in the various mining fields. The numbers multiplied by 100 represent the heating value on the moisture- and ash-free basis to the nearest 100 B.t.u. This figure is helpful in visualizing the considerable variation of western coal. The arrows point to mining fields.

UTILIZATION OF WESTERN COALS.

The relatively low current demand for western coal is not necessarily due to the lower rank but results mainly from the extreme competition with oil and gas. It is true that the high moisture content of much of the western coal penalizes long-distance transportation because the useless water adds to the weight and reduces the heating value. The high moisture also contributes to slacking and the relatively poor storage properties of the lignites and subbituminous coals. In the dry state, most western coals would have a high utili-

FIG. 9. Western coal fields and heating value of average coal on moisture- and ash-free basis.

zation value because they have favorable properties that contribute to easy utilization—they are noncoking and have relatively high reactivity.

Broadly speaking, the western coals are easier to handle in stokers and furnaces than are the higher-rank coking coals. They are free-burning and relatively low in sulfur and ash. For medium- and large-size furnaces, spreader-type stokers handle all the grades. Good performance and efficiency are also

obtained with chain-grate stokers, but they are not as popular as the spreader stokers. For domestic use in small underfeed stokers, there is probably no better solid fuel than oil-treated stoker coals having 13,800 to 14,500 B.t.u. per pound on the MAF basis. These free-burning coals rarely give any trouble in small stokers where they burn smokelessly with little carbon loss.

For large-scale industrial use, particularly for the manufacture of synthetic liquid fuel, the trend is toward pulverized coal. Because of the relatively high moisture content of coals lower than 13,800 heating value (MAF basis), it is necessary to predry for best utilization. The Bureau of Mines has developed improved methods for removing natural moisture from the lower-rank fuels which improves their utilization in the pulverized form. After drying, the lignitic and subbituminous coals can be pulverized with virtually half the energy required to pulverize the raw coal, and the performance of furnaces on the dried pulverized coals is almost equal to that on the highest-rank coals. The noncoking western coals can be carbonized readily at low temperatures in continuous retorts to yield valuable products of considerably higher heating value than the original coal. By heating the coal to about 1,100° F tars and light-oils amounting to approximately 18 percent of the heating value of the original coal can be obtained, and reactive smokeless chars amounting to about 72 percent of the heating value of the original coal are formed. These up-graded products from lower-rank coals may be attractive for industrial uses.

As our supplies of petroleum and natural gas decrease in availability and increase in price, the increased energy demand for all forms of fuel may have to be met by coal. We can look forward with assurance that the western coals are in ample supply and they can be converted to all forms of energy.

U. S. Bureau of Mines,
Coal Branch Region IV,
Denver, Colo.
March 13, 1950.

"PNEUMATOLYSIS" AND THE LIQUID INCLUSION METHOD OF GEOLOGIC THERMOMETRY.[1]

GEORGE C. KENNEDY.

ABSTRACT.

The writer believes that a more cautious attitude should be taken toward the acceptance of much of the recent work on the use of vacuoles in geologic thermometry. Temperature determinations by the decrepitation method may be widely in error. The correction for pressure is difficult to evaluate because of the inherent errors in estimating pressure in a hydrothermal solution. Further, most corrections due to pressure that have been made in recent published papers have been considerably in error because of the inadequacy of our knowledge concerning the P–v–T relationships in water. New pressure correction curves are presented. The fundamental assumption in the use of vacuoles is challenged. Most vacuoles are present along lineage boundaries in minerals and these boundaries may serve as paths along which material may move to and from the vacuole. Experimental evidence is cited to show that material can move readily along lineage boundaries or through a crystal structure into vacuoles.

INTRODUCTION.

The term "pneumatolytic" has been used in geologic literature infrequently in recent years. The general trend by economic geologists is to describe ore solutions as "hydrothermal" with the implication of "liquidity." This is exemplified by a paper [2] recently published in which F. Gordon Smith states, in regard to the Cornish tin deposits, "Therefore, the deposits were not formed by pneumatolysis, but by the usual hydrothermal liquids." Further along Dr. Smith says, "Having concluded that the Cornish tin deposits are not pneumatolytic in origin, the question arises: are there *any* pneumatolytic ore deposits?"

Dr. Smith's conclusions are based on measurements of the temperature at which vacuoles, partially filled with liquid, become completely filled. This is the method of Sorby [3] which has recently enjoyed a great upsurge in popularity. Smith and his students use a variation of Sorby's methods in that they determine the temperature at which the minerals decrepitate [4] presumably due to sharp rise in pressure when the vacuoles become filled with liquid. The de-

[1] Paper No. 116 published under the auspices of the Committee on Research in Experimental Geology and Geophysics and the Division of Geological Sciences at Harvard University.

[2] Smith, F. Gordon, Laboratory testing of "pneumatolytic" deposits: ECON. GEOL., vol. 44, pp. 624–625, 1949.

[3] Sorby, H. C., On the microscopical structure of crystals: Geol. Soc. London Quart. Jour., vol. 14, pp. 453–500, 1858.

[4] Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: ECON. GEOL., vol. 43, pp. 637–654, 1948. Smith, F. G. and Peach, P. A., Apparatus for the recording of decrepitation in minerals: ECON. GEOL., vol. 44, pp. 449–454, 1949. Peach, P. A., The decrepitation geothermometer: Am. Mineralogist, vol. 34, pp. 413–421, 1949.

crepitation is recorded either by means of stethoscope or by an appropriate electronic listening device.

Three of the six samples Smith reports upon are from St. Austell, Cornwall. The specimens are described as a vuggy intergrowth of tourmaline, cassiterite, and quartz. The temperatures of filling of the vacuoles are reported respectively as 345° C, 345° C, and 329° C. With the assumption that at the time of origin the solutions were under a pressure equivalent to two miles of rock, the temperatures of deposition are corrected by Smith to 390° C, 390° C, and 370° C.

Dr. Smith's conclusion from these data that the Cornish tin deposits are not pneumatolytic and his question "are there *any* pneumatolytic deposits?" are of such fundamental importance and are so far-reaching in their implications that it seems wise to examine critically certain of the assumptions involved.

At the outset the writer would like to state that he has nothing but admiration for the attempts of Smith and others to bring something of precision to the geologist's efforts to reconstruct the temperature and pressure history of an ore body. The questions that the writer wishes to raise are primarily intended as a caution against the too ready acceptance of far-reaching conclusions based on what appears to the writer to be insufficiently compelling evidence.

FUNDAMENTAL ASSUMPTIONS.

Certain assumptions are implied by Smith in the statement quoted above.

1. Deposits formed at 390° C and under a pressure equivalent to two miles of rock could not have been formed from a gas.
2. "True" pneumatolytic deposits could be detected by a decrepitation curve.
3. A reasonable correction to the temperature of disappearance, resulting from the pressure under which the deposits were formed, has been made.
4. The coefficient of expansion of vein-forming or ore-carrying solutions is the same as that of water.
5. The temperature of filling of a vacuole has a unique significance, that is, there has been no transport of material to or from the vacuole since its formation.

Various other assumptions are made, but they seem to be less serious. It is at once apparent that many of these assumptions are not unique with Smith; they have been stated or implied by most of the workers who have used vacuoles to determine the temperature of origin of deposits.

PNEUMATOLYSIS.

The first question is: Why could not these deposits formed at 390° C, if we accept Smith's value, have been pneumatolytic? Bunsen first introduced the term *Pneumatolysis*. He applied it to "those classes of deposits made up of the many products which form as a result of the influence of volcanic gases and vapors upon rocks" (writer's translation).[5]

[5] Bunsen, R., Gestein-bildung durch pneumatolysiche Metamorphose: Neues Jahrb., p. 863, 1851. Abstract from Bunsen, R., Über die Prozesse der vulkanischen Gesteins-Bildungen Islands: Poggend. Annalen, vol. LXXXIII, p. 197, 1851.

Bunsen apparently had in mind near-surface fumarole deposits of the type he had been studying at Hecla when he defined the term. However, Bunsen's restricted concept of pneumatolysis was antedated by Elie de Beaumont [6] and Daubrée,[7] who ascribed certain tin-ore deposits to the action of *"agents minéralisateurs* such as fluorine, chlorine, sulfur, phosphorus, silicon and boron [which] have the property of forming with the metals volatile compounds, which escape from the granite magma as gases with low critical temperatures." [8]

Bunsen's term "pneumatolysis" was almost immediately assigned to the concepts of tin-ore genesis as set forth by de Beaumont and Daubrée. Vogt [9] uses the term in this sense in his excellent discussions of the origin of tin deposits and extends the term to include apatite deposits genetically connected with gabbroic magmas.

In this century many geologists have used the term in the same sense as Vogt, Beaumont, and Daubrée. Fenner [10] with little change from Bunsen's original wording defined pneumatolytic as "pertaining to processes or results effected by gases evolved from igneous magmas or entrained with gases of that origin." More recently Bateman [11] uses the term in the same familiar sense. "If the pressure is such that a vapor phase is formed, high-temperature gaseous emanations are to be expected and pneumatolytic processes will prevail."

In none of the definitions is it implied that water vapor cannot be a dominant component of the pneumatolytic processes, though the major transporting agents are generally stated or implied to be "fluorine, chlorine, sulfur, and boron." The requirement throughout all these various definitions is that the introduced materials be transported as gas.

The writer wishes to make no particular brief for pneumatolysis. It seems that we are almost as ignorant now as we were in Bunsen's time of the actual importance of this mechanism. However, Smith's statement, from his observation that the Cornwall minerals decrepitated at 345° C, that the deposits were formed "by the usual hydrothermal liquid" seems to the writer to be unwarranted. Smith, *assuming* that the vacuoles are filled with water, deduces that the temperature of deposition was 390° C. However, at 390° C water would be gaseous, not liquid, as 390° C is above the critical temperature of water. Further, it appears possible that a hydrothermal solution consisting dominantly of water but with considerable quantities of volatile fluorine, chlorine, boron and sulfur compounds, might have a critical temperature even lower than that of pure water, 373.4° C. Smith may assume that a hydrothermal solution at 390° C carries a sufficient burden of non-volatile solutes, presumably as com-

[6] Elie de Beaumont, Sur les émanations volcaniques et métallifères: Soc. géol. France Bull., p. 1249, 1847.

[7] Daubrée, A., Du gisement, de la composition et de l'origine des amas de minerai d'étain: Annales des mines, vol. XX, 3rd series, p. 65, 1841.

[8] Hatch, F. H., The relation of geology to mining: Econ. Geol., vol. 9, p. 224, 1914.

[9] Vogt, J. H. L., Beiträge zur genetischen Classification der durch magmatische Differentionsprocesse und der durch Pneumatolyse entstandenen Erzvorkommen: Zeitschr. prakt. Geologie, pp. 145–156, 367–370, 444–459, 465–483, 1895.

[10] Fenner, C. N., Pneumatolytic processes in the formation of minerals and ores, *in* Ore Deposits of the Western States (Lindgren volume), p. 73, Am. Inst. Min. Met. Eng., New York, 1933.

[11] Bateman, A. M., Economic Mineral Deposits, p. 85, John Wiley and Sons, New York, 1942.

pounds of sodium and potassium, that it would be below its critical temperature, but this must remain only an assumption. In this respect it is interesting to note that sodium and potassium are introduced in the wall rock of the typical tin-ore deposit to a relatively lesser extent that into most other hypothermal and mesothermal deposits.

Another possibility remains. Smith implies [12] in two recent papers that he chooses to call all gases at supercritical pressures "liquids." Such terminology, however, is most unfortunate and can only lead to confusion. In such case he will have eliminated the possibility of pneumatolytic tin-ore deposits by definition, as almost all of them have probably formed under supercritical pressures..

TEMPERATURES AS DEDUCED FROM VACUOLES.

Of more importance, however, than the matter of terminology are certain of the assumptions underlying the use of vacuoles in geologic thermometry. Considerable care must be exercised in making the measurements of temperature of disappearance and in most cases the results are subject to varying interpretations. Some of the limitations of the method have been pointed out in part by Ingerson [13] and Peach [14] but do not seem to be widely appreciated.

Probably the most common method of vacuole study is the visual method in which a microscope with heating stage is employed. A glass dish is incorporated in the usual design of heating stage. The material to be studied is immersed in some suitable liquid of high boiling point, such as nujol, paraffin oil, or one of the silicone liquids, and a cover glass placed over the assembly. In most designs for heating stage, only the margins of the dish are wound with a heating element as the central portion of the dish must be left open for a light path. The entire apparatus is appropriately insulated. In such an apparatus, heating is only from the margins of the dish and cooling takes place dominantly from the central portion of the dish, the area under the microscope. As a consequence, sharp temperature gradients may be present within the immersion liquid. Under some experimental conditions where large slices of a crystal are employed and the circulation of the liquid is slight, the writer has noted temperature differences of as much as 40° C in the liquid. If temperatures are measured with an ordinary bulb thermometer at a fixed position in the liquid, considerable errors will result. Vacuoles near the margin of a large plate in the liquid will thus apparently disappear at lower temperatures than those nearer the center of the state. Appropriate precautions must be taken and the error in measurement, even under the best conditions, may be as much as several degrees.

The second method employed in determining the temperature of filling of vacuoles is that of the decrepitation curve. This method depends upon the change in the rate of increase in pressure once the solution in the vacuole has

[12] Smith, F. G., Transport and deposition of the non-sulphide vein minerals. III. Phase relations at the pegmatitic stage: Econ. Geol., vol. 43, pp. 535–546, 1948. Reply to discussion by George Morey: Econ. Geol., vol. 44, pp. 741–742, 1949.

[13] Ingerson, E., Liquid inclusions in geologic thermometry: Am. Mineralogist, vol. 32, pp. 375–388, 1947.

[14] Peach, P. A., op. cit.

expanded with increasing temperature and the vacuole has become filled. Some examples are illustrated by Figure 1 in which the curves for temperature versus pressure are shown for three hypothetical vacuoles. The first curve is for the pressure history of a vacuole which becomes filled with liquid at 180° C. The second curve is for a vacuole that becomes filled at 340° C and the third

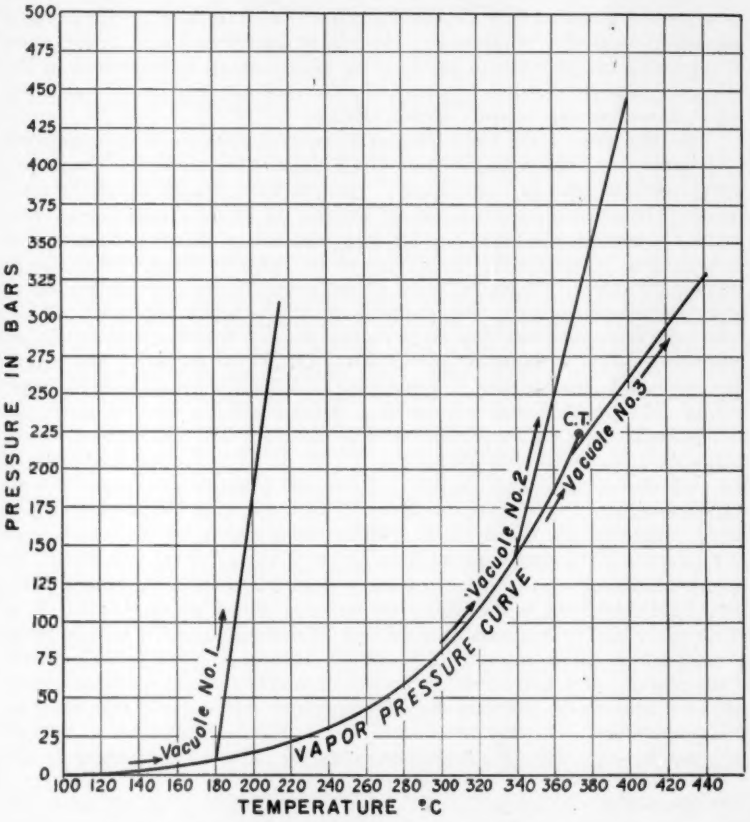


FIG. 1. Pressure-temperature history for various vacuoles.

curve represents the case of a vacuole in which the amount of liquid per unit volume in the vacuole is less than that for liquid at its critical density. Examination of Figure 1 indicates at once the limitation of the decrepitation method. The sharp rise in pressure with increasing temperature when the vacuole becomes filled at 180° C is noted. However, conditions at 340° C are considerably different. The pressure in the vacuole is already changing rapidly with

temperature along the vapor-pressure curve. There is no sudden change in the rate of pressure increase once the vacuole becomes filled and it is doubtful if the change in the number of explosions in the decrepigraph would be sufficiently great to locate closely the nick-point in the pressure-temperature curve. In the third case under consideration there is a *decrease* in the rate of pressure rise once the fluid in the vacuole becomes homogeneous. This would be the case for any pneumatolytic deposit formed at supercritical temperatures and subcritical pressures. With such a mineral, no significance as to temperature of formation can be given to any increase in the rate of decrepitation, as the mineral is heated. Yet it is by means of a decrepigraph that Smith is attempting to show that such deposits do not exist.

The difficulties in the interpretation of decrepigraphs are at once apparent by examination of the graphs published by Smith and his students. The graphs for cryolite and siderite from Ivigtut,[15] reproduced in Figure 2, may be compared. The problem here is to decide whether the first few explosions represent the temperature of filling or whether a later sudden change in frequency of of explosions represents the point at which the vacuoles become filled. Scott selected for siderite the 160° C point where a sudden change in the frequency of explosions takes place. For pyrite, however, he selects the point 115° C where the first explosions take place, though it seems that he might equally as well have selected the point at approximately 225° C where there is also a sudden increase in the number of explosions analogous to the siderite decrepigraph. The writer wishes to emphasize that this extreme uncertainty in the interpretation of the decrepigraph occurs here in a low temperature region where the method works, at least in theory. At the higher temperatures where the method no longer works in theory the results from the graph can have no significance as to temperature formation. One could, with almost equal confidence, select any one of four vastly differing temperatures for the temperature of formation of the smoky quartz from Hybla. The graph for the Pointe du Bois beryl, though this is one of the sharpest and most clean-cut graphs of all those figured by Scott, is obviously meaningless as the temperature of 390° C is above the critical temperature of water and the pressure can only be increasing at a uniform or decreasing rate as shown for vacuole No. 3 in Figure 1. Even if the vacuole were filled with a relatively concentrated salt solution, essentially no break in the pressure versus temperature curve would take place at this temperature. That the curve for beryl was of little significance as to temperature of origin was, of course, understood by Scott who elsewhere in the article states "It should be noted that fluid inclusions yield results of value . . . only when their overall density exceeds the critical density of the solution." The writer has been, perhaps, not entirely fair to the decrepitation method by citing these four diagrams from the twelve that Scott reproduces. The other diagrams, all but one of which are for low temperature, give results which are somewhat more clean cut, and in three cases, where an independent check on the temperature of filling of the vacuoles had been obtained, the decrepigraph indicated temperatures that are within 25° C of correct. It is

[15] Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: Econ. Geol., vol. 43, p. 645, 1948.

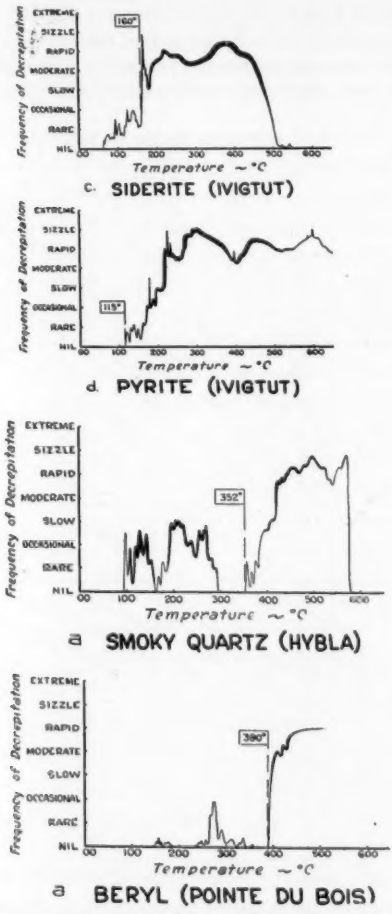


FIG. 2. Decrepigraphs of various minerals.

readily apparent, however, that at temperatures approaching the critical, a greal deal of personal interpretation may go into reading such graphs.

CORRECTION DUE TO PRESSURE.

Ingerson [16] has presented some curves for the correction for pressure at time of deposition of the temperature of disappearance of the vapor phase.

[16] Ingerson, E., Liquid inclusions in geologic thermometry: Am. Mineralogist, vol. 32, pp. 382–383, 1947.

These curves are based on a compilation of water data by O. F. Tuttle. The curves are testimony to our lack of data at that time concerning the P-v-T relations of water at these temperatures and pressures. Though the volume of water must increase with increasing temperature, the curves show decreasing

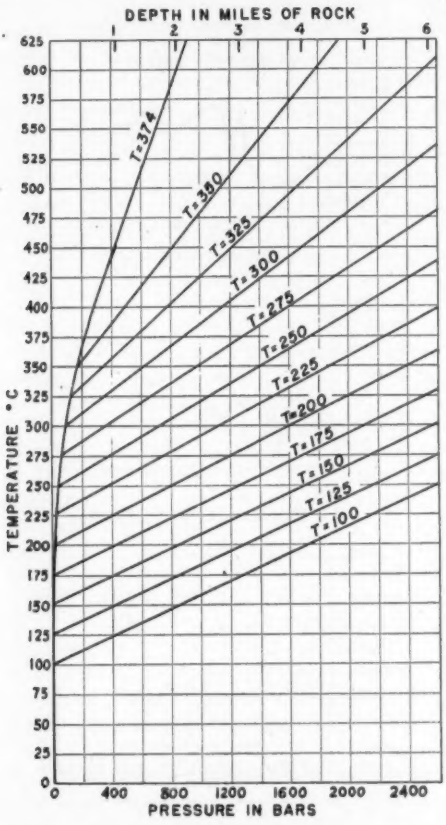


FIG. 3. Curve showing relation of temperature of disappearance and pressure at time of formation.

compressibility for water with increasing temperatures. In Ingerson's plot of temperature versus pressure, the curve at 300° C and 500 kg/cm becomes almost horizontal, indicating that in this pressure-temperature region water has zero compressibility or an infinite thermal coefficient of expansion, either of which seems improbable. Because of these and other apparent anomalies in the

reported properties of water, the writer has recently remeasured the P-v-T relations of water over an extended pressure and temperature range.[17]

Two new charts, Figures 3 and 4, are presented based on these newly determined P-v-T relations. The charts are analogous to those presented by

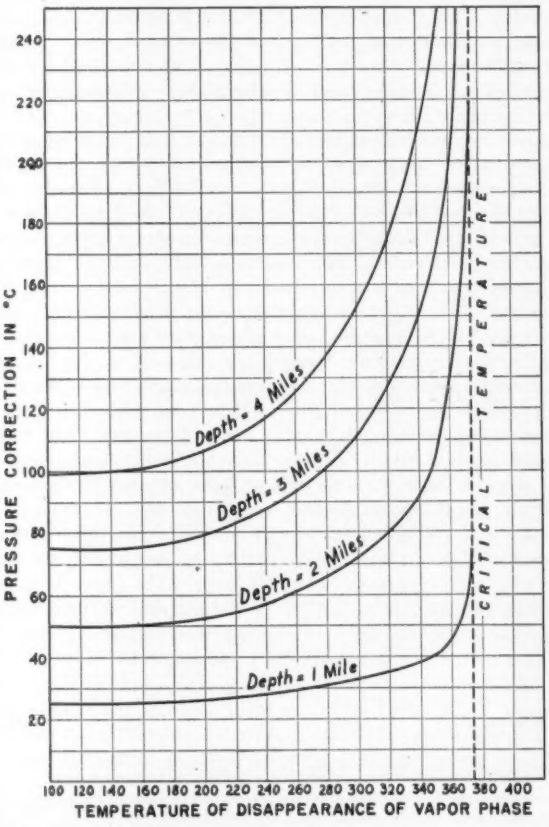


FIG. 4. Correction to be added to temperature of disappearance depending on pressure at time of formation.

Ingerson. Figure 3 shows the temperature of formation of the mineral when the pressure can be estimated and the temperature of disappearance of the vapor phase is known. Figure 4 shows the pressure correction when the pressure at the time of formation is known and the temperature of disappearance

[17] Kennedy, G. C., Pressure-volume-temperature relations in water at elevated temperatures and pressures: Am. Jour. Sci., vol. 248, August 1950.

of the vapor phase is known. The charts presented are in approximate agreement with Ingerson's charts at the lowest temperature shown, 100° C. At the higher temperatures, however, the corrections are in major disagreement. Ingerson's charts show a correction of about 55° C for deposits formed at a depth of 7 km and a temperature of approximately 300° C. The corresponding correction taken from Figure 4 presented here is about 165° C.

Smith has postulated that the St. Austell, Cornwall, minerals formed under a pressure equivalent to two miles of rock. The correction for this depth is approximately 95° C, so his estimated temperature of formation must be raised from 390° C to 440° C.[18]

It is apparent from examination of Figure 4 that when the temperature of disappearance of the vapor phase approaches the critical temperature, uncertainties in estimating the pressure at the time of formation and uncertainties in estimating the temperature of disappearance of the vapor phase may influence very greatly the deduced temperature of formation. We may take the St. Austell tin deposits as an example. It seems highly unlikely that the temperature of disappearance of the vapor phase can be estimated from a decrepigraph to within 20° C. More precise results may be obtainable at lower temperatures, but at 345° C the rate of change of pressure with temperature once the vacuole has become filled is not nearly as great as at the lower pressures. Likewise, it seems impossible that the pressure at the time of formation can be estimated to within much better than 100 percent. The uncertainty in estimating pressure has been clearly pointed out by Ingerson [19] who states "Errors [in estimating depth of cover] will vary from negligibly small to a factor of several fold." Furthermore, even though we know the depth of cover, estimated as two miles by Smith for St. Austell, we do not know the pressure. Under a depth of cover of two miles the pressure may range from hydrostatic, the weight of a two-mile column of water, to lithostatic, the weight of a two-mile column of rock, or to something greater than lithostatic. The pressure might be more than lithostatic in case the deposits were formed close to their magma source and high pressures of volatiles had resulted from partial crystallization of the magma. This possibility is discussed at some length by Morey.[20] It seems to the writer that any estimate of the pressure at the time of the formation of a mineral deposit might very likely be in error as much as or more than 100 percent. We may take, then, the uncertainty as to temperature of disappearance of the vapor phase and the uncertainty as to pressure at time of formation of the

[18] Smith obtains 390° C by adding a correction of 45° C, presumably taken from Ingerson's charts, to the temperature of 345° C obtained from the decrepitation curve. Scott, one of Smith' students, has published a compilation of water data from which the correction due to pressure may be read. Scott's (Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: ECON. GEOL., vol. 43, p. 640, 1948.) curves indicate a correction of approximately 70° C from which the final temperature would be 415° C. Scott's compilation of water data is excellent in that he has recognized the essentially straight-line relationship of pressure plotted against temperature at constant volume. His pressure values tend to be a little high for any given temperature and density.

[19] Ingerson, E., op. cit., p. 386.

[20] Morey, G. W., The development of pressures in a magma as a result of crystallization: Washington Acad. Sci. Jour., vol. 12, pp. 219–230, 1922. Relation of crystallization to the water content and vapor pressure of water in a cooling magma: Jour. Geology, vol. 32, pp. 291–294, 1924.

St. Austell deposits and determine the range of possible temperatures under which the deposits might have formed. Reference to Figure 4 shows that the maximum temperature is 665° C. (A pressure correction of 300° C is added to a temperature of disappearance of 365° C.) The minimum temperature of formation is 360° C. (A pressure correction of 35° C is added to a temperature of disappearance of 325° C.)

In summary, then, it seems that about all that can be said about the St. Austell deposits, based on the assumptions made to date and their probable limit of error, is that the deposits formed at some temperature between 360° C and 665° C. It is impossible to say whether they were pneumatolytic, that is, formed from gases under high pressures, or were formed from the usual hydrothermal liquid.

COMPOSITION OF LIQUID IN VACUOLES.

The writer has assumed throughout the foregoing discussion that the liquids which fill the vacuoles in minerals are pure water. This, certainly, is not the case. Figures 3 and 4, which show the temperature correction due to pressure at the time of formation of the vacuole, are based on the supposition that the coefficient of thermal expansion and the compressibility of the solution in the vacuole are the same as that for pure water. In so far as the solution in the vacuoles contains dissolved materials with a higher critical temperature than that of pure water, the pressure correction will be somewhat smaller than that for water. On the other hand, if the solution in the vacuoles contains dominantly dissolved gases, such as CO_2 and H_2S, or volatile fluorides with low critical temperature, the pressure correction may be greater than that for pure water. Ingerson has recently discussed some aspects of this problem.[21]

STABILITY OF VACUOLES.

The basic assumption in the use of vacuoles remains to be evaluated. The entire technique hinges on the belief that the vacuoles contain a true sample, as to composition and quantity per unit volume, of the vein-forming fluid, that is, that nothing has entered or left the vacuole since the time of its formation. Is this a valid assumption in view of the known mobility of ions and molecules such as water? All geologists are familiar with the fact that, with sufficient time, slowly moving solutions can completely fill gas cavities in seemingly dense lavas with opal and chalcedony. Under these circumstances, however, the solutions have available the minute inter-granular boundaries in the lavas which serve as paths along which the solutions may move. However, it is now known that discontinuities in a crystal structure are exceedingly numerous. Lineage boundaries are common and have been discussed by Buerger.[22] Because of these discontinuities between units which go to make up a crystal the strength of a crystal is much less than is to be expected from theoretical considerations. Buerger states [23] "The experimental strength is greater than

[21] Ingerson, E., op. cit., pp. 378–380.
[22] Buerger, M. J., The significance of "block structure" in crystals: Am. Mineralogist, vol. 17, pp. 177–191, 1932.
[23] Buerger, M. J., op. cit., p. 186.

usual, however, when tested on pieces of order of magnitude of 10^{-5} or 10^{-6} cms, from which it has been concluded that this is about the spacing of the surface cracks." Buerger believes the cracking to be a cause of lineage formation. In another paper he points out the relation of lineage structure to the vacuoles in a crystal.[24] He says "Examination of a large number of crystal cavities of different types brings out the fact that a considerable proportion of them occur obviously in lineage boundaries. . . . It appears very probable that most, or perhaps all, of the negative crystals do actually occur in lineage boundaries, and that those which do not show an obvious connection with this feature, probably would if a cleavage somewhat above or below the one under examination could be seen." Somewhat further along he states ". . . crystals rich in lineages are also rich in irregular negative crystals." Buerger uses the term "irregular negative crystals" as the general descriptive term for vacuoles in single crystals. Elsewhere in considering pyrite Buerger [25] speaks of "complex interlineage cavities similar to those already described for galena."

A variety of experiments indicate that the interlineage cracks are of breadth sufficient to serve as channel-ways for the migration of gases and liquids. Buerger,[26] in citing the well-known fact that experimentally determined densities of minerals are commonly less than densities calculated from X-ray data, says "The explanation is almost certainly that the interlineage spaces of various sorts increase the apparent volume of the material." Part, but not all, of the discrepancy noted by Buerger is due to the fact that the X-ray wave lengths used prior to about 1941 were low by .00002 percent. However, Buerger's basic assumption still stands. Dean, Gross, Brighton and Clair [27] have accounted for some anomalies in the absorption of hydrogen sulfide gas. They explain abnormally high absorption of gas in proportion to the surface area of galena crystals by assuming that the interstitial surfaces along lineage boundaries are available for absorption. The effect disappears only when the size of the crystal is reduced to a fraction of a millimeter, the size of the individual lineage blocks. Barnes [28] found that rock salt which has been thoroughly wet and then dried externally, gave the infrared absorption band characteristic of water which indicated that water still remained in the interior. Joffe [29] has obtained some evidence as to the size of the cracks. From considerations as to the effect of cracks on the strength of the crystals, he computes that the "crevices may have dimensions of" 100 to 1,000 Angstrom units. In comparison a water molecule has a radius of approximately 1.4 Angstrom units. Joffe [30] also notes that some rock salt crystals, originally brittle, may behave plastically once they have been immersed in water. Such behavior is resultant from penetration and retention of water in the minute cracks in the crystal. The water

[24] Buerger, M. J., The negative crystal cavities of certain galena and their brine content: Am. Mineralogist, vol. 17, pp. 228–233, 1932.

[25] Buerger, M. J., Fluid inclusions in pyrite: Am. Mineralogist, vol. 19, p. 605, 1934.

[26] Buerger, M. J., The lineage structure of crystals: Zeitschr. Kristallographie, vol. 89, pp. 195–220, 1934.

[27] Dean, R. S., Gross, J., Brighton, T. B., and Clair, H. S., The nature of mineral-gas systems: U. S. Bur. Mines, 1933.

[28] Barnes, R. B., The plasticity of rock salt and its dependence upon water: Phys. Rev., vol. 43, pp. 82–83, 1933.

[29] Joffe, A. F., The Physics of Crystals, p. 61, McGraw-Hill Book Co., New York, 1928.

[30] Joffe, A. F., op. cit., p. 63.

may later be removed, as the crystals will return with time to their initial brittle condition. The cracks between lineage units are sufficiently small, however, so that only in exceptional cases can they be observed, even at the highest powers, under a petrographic microscope. Furthermore, the differences in orientation between adjacent lineage units may be sufficiently minute that they will be revealed only by the most careful illumination of a cleavage face. The apparent simultaneous extinction of all parts of a crystal under the crossed nicols of a polarizing microscope, is no indication that the lineage units do not exist. They are the rule, rather than the exception.

It is also possible that water may diffuse into or out from the vacuole of a crystal through the crystal structure. Many crystal structures, such as those of the zeolites and of layer-type silicates, have tubular or planar channel-ways several times the diameter of a water molecule. The phenomena of base-exchange and of zeolitic variation in water content are familiar examples of the permeability of some seemingly "solid" crystal structures. The size of these channelways, however, would not be necessarily a controlling factor. Students of replacement phenomenon, who are familiar with the marvelously selective manner in which certain zones in a crystal may be replaced, find it difficult to doubt that wholesale transfer of material through a crystal structure may take place. The boundaries between lineage and mosaic units, however, undoubtedly form more ready paths to and from vacuoles than do the interstructure spacings.

There is, in addition, certain experimental evidence that material can be moved into and away from vacuoles. Ingerson [31] states "It is not uncommon to observe an increase in the diameter of a bubble during heating, which, of course, indicates leakage. It is by no means as simple to determine whether leakage has taken place before heating." Ingerson follows this by saying "If all of the inclusions in a given plate show very nearly the same degree of filling, the chances are that little leakage has occurred." Although the writer is in agreement with most of Ingerson's remarks, he cannot agree with this latter statement for reasons which will be discussed shortly.

Leakage, of the sort noted by Ingerson, is commonly observed in working with liquid inclusions. However, most of it takes place during the few minutes or few hours while the specimen is being heated upon the microscope stage and the internal pressure in the vacuole is high. Might it not be that with the vastly longer geologic times, even those vacuoles which apparently did not leak in the few minutes of heating would leak until their internal pressure came into harmony with the pressure surrounding the mineral? In most cases, though not in all cases, there seems to be too *much* liquid in vacuoles rather than too little, as the temperature of origin as indicated by vacuoles is lower than general theory would suggest. The temperatures Ingerson finds for the pegmatitic quartz he has studied range from 67° C to 182° C. We find a ready explanation for a postulated excess liquid in vacuoles if we consider the temperature-pressure history of a vein. It seems likely that a vein is formed at temperatures considerably greater than the surrounding rock temperatures, as heated solu-

[31] Ingerson, E., Liquid inclusions in geologic phenomenon: Am. Mineralogist, vol. 32, p. 385, 1947.

tions are moving up a channelway from a high-temperature magmatic source. Once the flow of solutions from the magmatic source has ceased, the vein will cool to the surrounding rock temperature and the pressure within the vacuoles, initially in equilibrium with the external pressure, will drop as the liquid cools and contracts, but the pressure of the solution external to the crytals may not so drop. As the solution moving up the vein diminishes in quantity during waning hydrothermal activity, it will diminish in temperature, losing a greater proportion of its heat in transit and presumably coming from a cooling magmatic source. However, the pressure in many cases may remain much the same, due largely to the superincumbent load of rock or liquid as the case may be. Consequently, we can envision that in the usual course of events there will be a period, after the formation of a vein and before sufficient erosion has taken place to significantly change the load, when there will be high external pressures of liquid on a mineral and lower pressures inside a vacuole in the mineral. Under these conditions of pressure gradient there will be a tendency for material to migrate into the vacuole and some new balance between internal and external pressure, characteristic of the changed environment, will take place. The new balance will be a function of earth temperature, external pressure and availability of surrounding solution under that external pressure. Erosion may later uncover the mineral with the preserved secondary balance, characteristic of some stage in the history of the mineral. Under ordinary conditions the amount of liquid in the vacuoles may not be changed unless sharp differences between internal and external pressure are present. Such differences are not likely to result once the mineral comes into the low pressure and low temperature environment near the surface of the earth. Relative uniformity of liquid content in the vacuoles seems to indicate not necessarily little or no leakage as postulated by Ingerson, but a long period at one temperature and pressure during the history of the mineral in which equilibrium was established.

There is some experimental evidence to indicate that solution may be readily moved into vacuoles. Mr. James Grunig, now of the U. S. Geological Survey, worked in the writer's laboratory during the summer of 1948. A plate of fluorite approximately 2 mm thick was prepared and the temperature of disappearance of the vapor phase was determined for a number of vacuoles, which, by position or shape, could be later readily identified. The temperatures were of the order of 200° C. The plate was then placed in a bomb and subjected to a pressure of approximately 1,500 bars of water for a few minutes and reexamined. Little change was noted in the vacuoles. The plate was again placed in the bomb, the temperature was raised to 150° C and a water pressure of 1,500 bars was applied for a period of approximately two weeks. At the end of this time it was noted that the temperature of disappearance of the vapor phase in those vacuoles reexamined had been lowered approximately 10° C. A second experiment was made in which cleavage fragments of fluorite were employed. In this experiment the diameter of the gas bubble in the fluorite plate was measured under the microscope by use of a micrometer ocular before and after pressure treatment. In every case a distinct decrease was noted in the diameter

of the bubble after pressure treatment. Liquid had certainly moved into the vacuoles.[32]

CONCLUSION.

In conclusion, the writer has been concerned in the last few years by the apparent trust placed in the use of vacuoles in geologic thermometry. Certain minerals which we have long believed to be high temperature, such as pegmatitic quartz and quartz in granite, have vacuoles which indicate low temperatures. Further, deposits which we have long believed, on what seems good grounds, to be low temperature, such as the Mississippi Valley lead-zinc deposits and some sedimentary salt deposits, have some vacuoles which indicate relatively high temperatures. Some students have suggested, on the basis of these findings, that our concepts of geologic temperatures might need revision. To this writer it seems more likely that it is our fundamental assumptions in the use of vacuoles in geologic thermometry that need revision.

GEOLOGICAL MUSEUM,
HARVARD UNIVERSITY,
CAMBRIDGE, MASS.,
April 24, 1950.

[32] This information has been transmitted orally by Mr. James K. Grunig. The details and results of these extremely revealing experiments are being prepared for publication.

BIOGEOCHEMICAL INVESTIGATIONS IN THE TRI-STATE DISTRICT.

JOHN W. HARBAUGH.

ABSTRACT.

Samples of various plants were collected at seven areas in the Tri-State Mining district. These samples were analyzed colorimetrically for zinc and copper and analyzed spectrographically for lead, nickel, tin, silver and cobalt. Higher average zinc concentrations were found in plants growing near mineralized zones less than 100 feet in depth. Analyses of 56 samples of twigs of the blackjack oak, *Quercus marilandica,* from trees growing above or near mineralized zones, showed an average zinc concentration 29 percent greater than 101 similar samples gathered in the same area, but at a distance of 300 feet or more from mineralized zones. In addition, the samples from above or near mineralized zones showed an average zinc concentration 67 percent greater than 23 similar samples collected in areas presumably barren of mineralization and lying some miles distant.

Samples of 24 species of trees, collected above mineralized zones, showed an average zinc concentration 38 per cent greater (in leaves) and 25 percent greater (in twigs) than similar samples from areas barren of mineralization. Samples of 16 species of grasses and herbaceous plants, gathered above mineralized zones, showed an average concentration of zinc 30 percent greater than similar samples from barren areas.

In a two square mile area, the geographical distribution of zinc concentration in samples of *Quercus marilandica* twigs showed moderate correlation with known mineralized zones. Other metals showed much less correlation.

Biogeochemical surveys based upon average zinc concentrations from large numbers of plant analyses appear to offer promise in prospecting for concealed mineralization in the Tri-State district, particularly within the outcrop area of the "Boone" limestone.

INTRODUCTION.

THE Tri-State district has been the scene of various attempts in the past twenty years to utilize geophysics and soil analysis in prospecting, all of which have met with little success.[1] Early in 1948, Dr. R. M. Dreyer, of the University of Kansas Department of Geology, proposed that the role of vegetation as a guide in prospecting be investigated. Through his efforts, the Research Foundation, of the University of Kansas, agreed to sponsor such an investigation.

Initially the problem was attacked in two ways: first, to discover if variations in plant ecology could be used as a guide to underlying zinc and lead mineralization; and, second, to measure the concentration of zinc and other heavy metals in plants to determine if significant differences exist in plants growing above or near zones of mineralization as contrasted with plants growing in areas presumably devoid of mineralization. As field work in 1948 gave

[1] Jakosky, J. J., Dreyer, R. M., and Wilson, C. H., Geophysical investigations in the Tri-State zinc and lead mining district: Kansas Geol. Survey Bull. 44, 151 pages, 1942.

little hope that variations in plant ecology could be used in prospecting, all further work was based on the determinations of traces of metals in plants. Samples of various species from selected localities were analyzed for zinc and copper by colorimetric means. Analyses for lead, nickel, tin, silver and cobalt were made with the spectrograph.

Acknowledgments.—Dr. R. M. Dreyer gave advice and was consulted throughout the work. Dr. J. O. Maloney, Dr. C. E. Grothaus, Mr. Morris Teplitz, Mr. Arthur Inman and Mrs. Addington, all of the Research Foundation, supplied a great deal of administrative and technical advice. Mr. John Awald and Mr. William Brite served as laboratory assistants, performing many of the analyses. The plants were identified by Dr. W. H. Horr and Mr. Ronald McGregor, of the Department of Botany. The author is indebted to them for their invaluable aid.

Mr. Robert Stroup, Mr. Joseph Lyden and Mr. Earl Gordon, of the Eagle-Picher Mining and Smelting Company, made available the drill logs and maps of the company, which formed the basis for selecting several of the investigated areas. Mr. Ward Ball, of the Federal Mining and Smelting Company, and Mr. Lauren Keenan, of the Harris Mining Company, supplied additional drilling information. Mr. George M. Fowler, consulting geologist, gave advice on a variety of problems.

Through the generous cooperation of Dr. John R. Musgrave, the spectrographic analyses were performed in the Research Laboratories of the Eagle-Picher Company, at Joplin, Missouri. The analyses were made by Mr. James S. Bryson and Mr. Virgil Granger, of the laboratory staff.

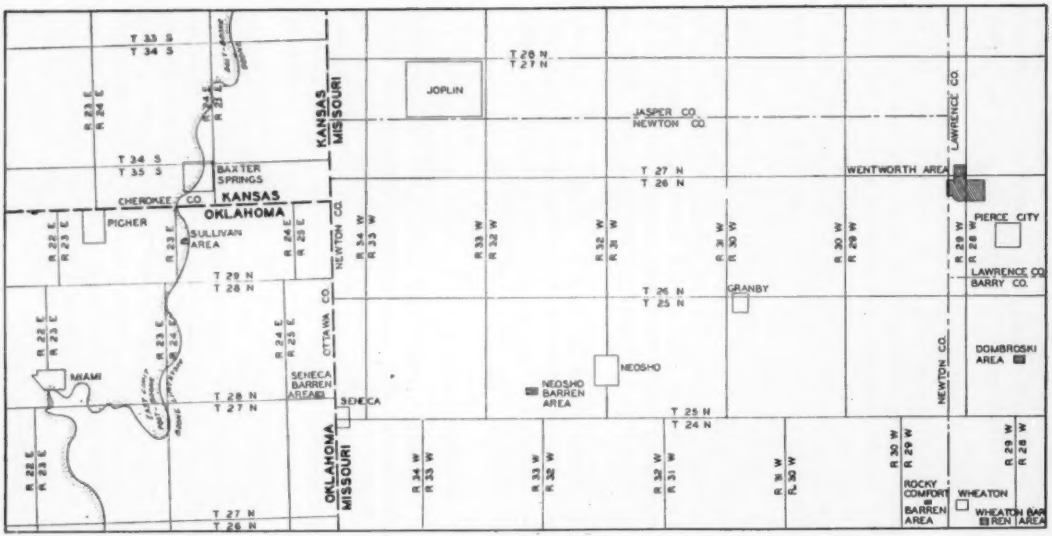
GEOGRAPHY AND GEOLOGY.

The Tri-State district is located in southeastern Kansas, southwestern Missouri and northeastern Oklahoma. The biogeochemical investigations were conducted principally in Newton, Barry and Lawrence Counties, Missouri, and to a lesser extent in Cherokee County, Kansas and Ottawa County, Oklahoma, as shown in Figure 1. The Missouri counties offered the best localities for biogeochemical investigation, namely, forested areas with shallow underlying mineralization, in which there has been relatively little mining activity.

The rainfall of slightly more than forty inches [2] and the latitude place the Tri-State district in the Austral life zone. Botanically, the district may be divided into two major ecological groups: the Ozark forest and the bluestem prairie. The Ozark forest is confined to soils derived from the middle Mississippian cherty limestones, known collectively as the "Boone" limestone, while the bluestem prairie occurs on soils derived both from the "Boone" limestone and the Pennsylvanian Cherokee shale. The Ozark forest is dominated by an association of oaks and hickories, with numerous lesser trees, including sassafras, juniper, elm, walnut, hackberry and river birch. The bluestem prairie is made up of tall grasses and herbaceous plants.

The ore deposits of the Tri-State district are contained almost entirely within the "Boone" limestone, which is the local designation of the group

[2] Flora, S. D., Climate of Kansas: Kansas State Board of Agriculture Rept., p. 26, 1948.



REGIONAL MAP OF TRI-STATE DISTRICT
SHOWING AREAS OF BIOGEOCHEMICAL STUDY

FIG. 1.

formed by the Warsaw, Keokuk, Reed's Spring and St. Joe limestones, of upper middle and lower middle Mississippian age. The "Boone," which is about 300 feet thick, is overlain by a thin remnant of upper Mississippian, the Carterville formation, consisting of shale, sandstone and limestone. Overlying the Carter-

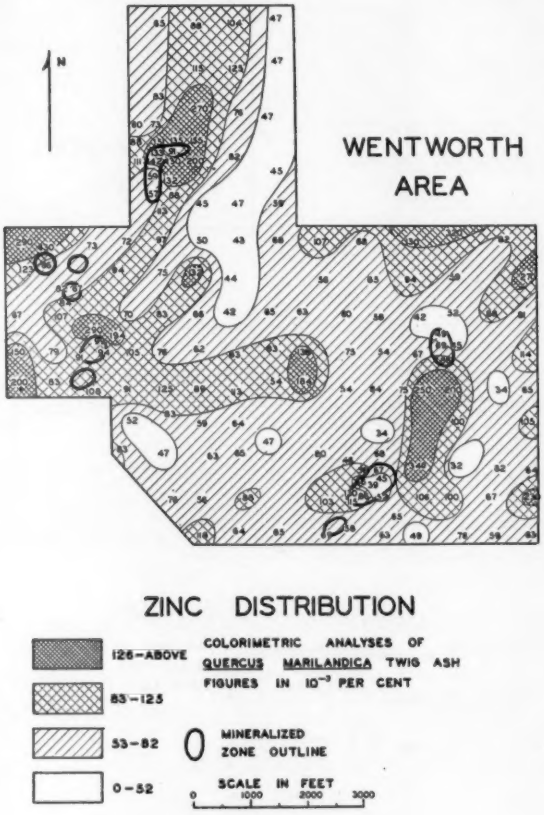


FIG. 2.

ville is the Pennsylvanian Cherokee shale, which commonly is not separated from the Carterville in prospecting.

The strata have a regional dip to the west-northwest, away from the Ozark uplift, of about 15–20 feet to the mile. Consequently the ore-bearing "Boone" limestone, which is exposed in the eastern three-fourths of the district, is covered by overlapping Pennsylvanian shales in the western portion of the district.

The principal ore minerals are sphalerite and galena. Pyrite and marcasite,

with small amounts of chalcopyrite, accompany the ore. The mineralization generally is accompanied by brecciation and chertification of the surrounding limestone, and, locally, by dolomitization. The ore bodies are of two types, "runs" and "sheet ground." The "run" type is an elongated deposit with rela-

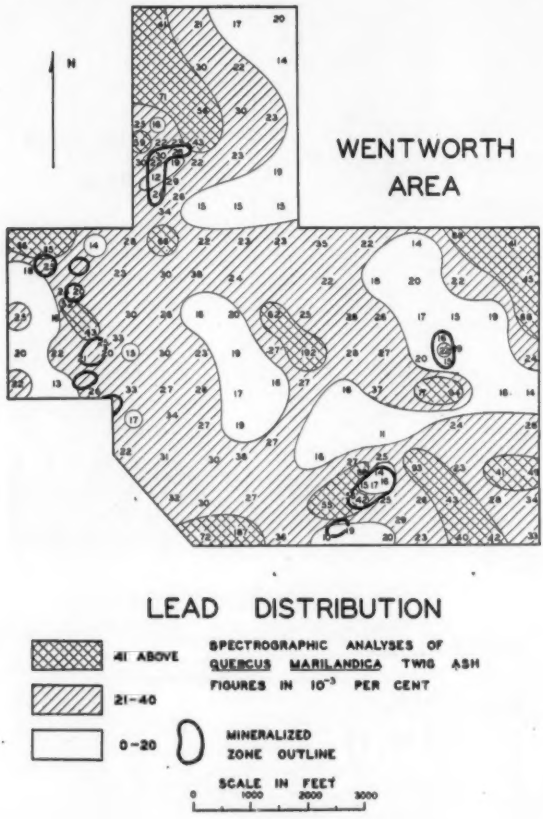


FIG. 3.

tively large vertical dimensions. The "sheet ground" type is a tabular body, sometimes with a horizontal extent of many acres, and of very limited vertical extent. All gradations exist between "run" and "sheet ground" deposits. The ore deposits are highly irregular in outline and show considerable variation in total sulfide content as well as in the ratio of zinc to lead. The commonly mined grade of ore contains from 2% to 4% zinc and 1% lead or less, although the ore may, locally, be much richer.

Ore bodies occur in those parts of the district which have been subjected to pre-mineralization flexing, shearing and brecciation. Fowler [3] states that "in the Tri-State district the degree and character of structural deformation appear to have controlled the size, shape, and richness of every ore deposit."

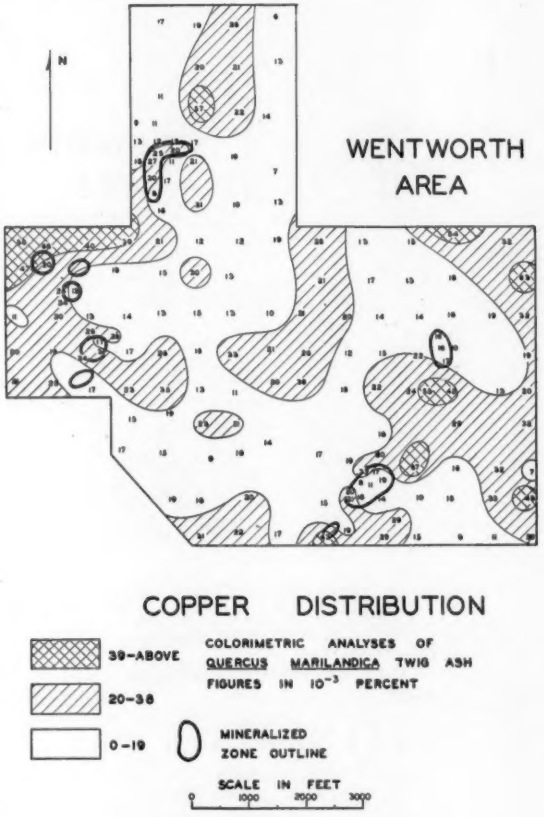


FIG. 4.

BASIS FOR BIOGEOCHEMICAL INVESTIGATIONS.

This attempt to correlate the heavy metal concentration in vegetation and subsurface mineralization is of necessity empirical. Since the heavy metal concentration of plants is partially a function of soil and lithological conditions,

[3] Bastin, E. S., et al., Contributions to a knowledge of the lead and zinc deposits of the Mississippi Valley region: Geol. Soc. America Special Paper 24, p. 55, 1939.

anomalous amounts of metals in plants may be a reflection of geochemical anomalies. Some of the conceivable causes of anomalous metal concentrations in vegetation in the Tri-State district are: (a) Precipitation of minor amounts of metals from mineralizing solutions which may have emanated from the main

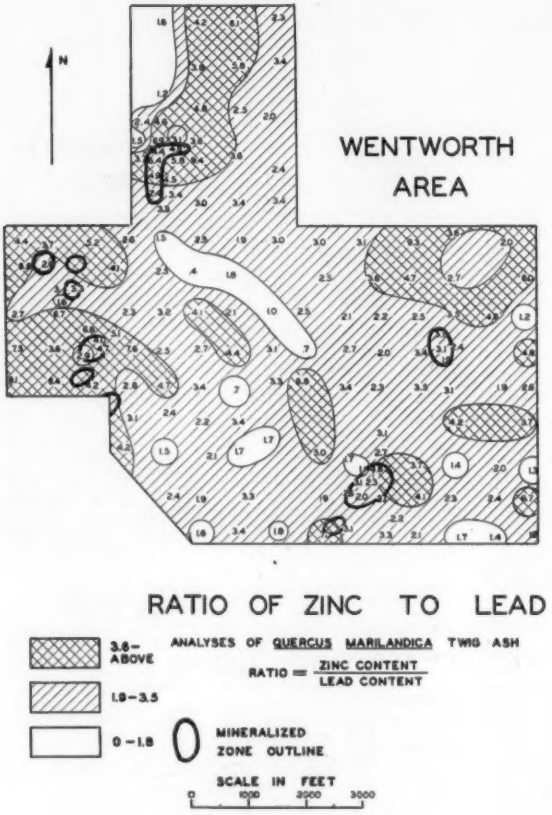


FIG. 5.

ore zones during the period of mineralization. In this way, the overlying rocks and, subsequently, the weathered derivatives may have become enriched with heavy metals which may be taken up by the plants. (b) Precipitation of minor amounts of metals that have been leached and carried upward from mineralized zones by circulating ground waters subsequent to ore deposition. (c) Actual contact of plant roots with shallow zones of mineralization. (d) Local chemical or lithological variations in the rocks or soils not related to mineralization.

(e) Local variations of drainage that might produce differential leaching or concentration by precipitation of metals in the soil.

Anomalies produced by the precipitation of minor amounts of metals from mineralizing solutions or ground water might be related to mineralized zones

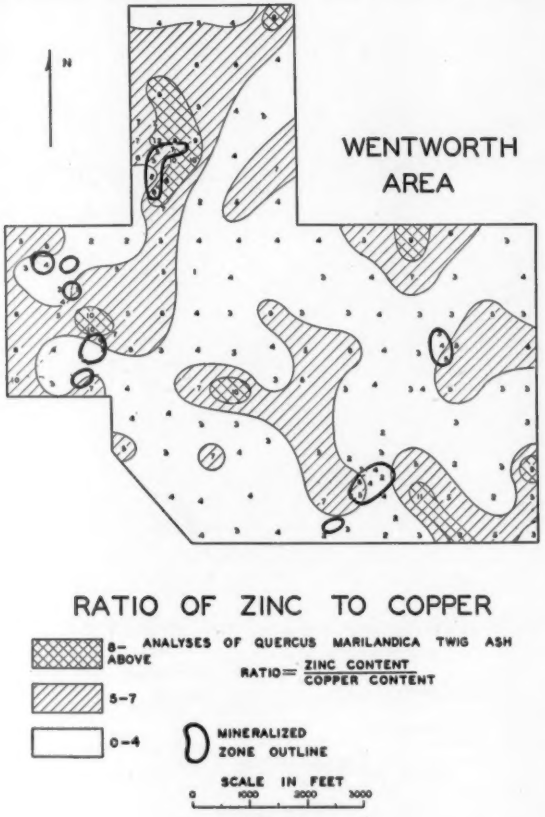


FIG. 6.

and possibly used as guides in prospecting. Anomalies caused by variations in lithologic or soil conditions unrelated to mineralization and those due to drainage conditions would be of no value in prospecting and might tend to mask anomalies caused by mineralized zones.

AREAS INVESTIGATED.

Each area selected for investigation has demanded a compromise of (a) the availability of sufficient information to determine the presence or absence of

mineralization, (b) the presence of a suitable natural and undisturbed vegetative cover, and (c) the absence or relative unimportance of sources of contamination, such as tailings piles.

Mineralized Areas.—The Wentworth area, of Lawrence County, Missouri, lies immediately northeast of the once active mining field that existed near the

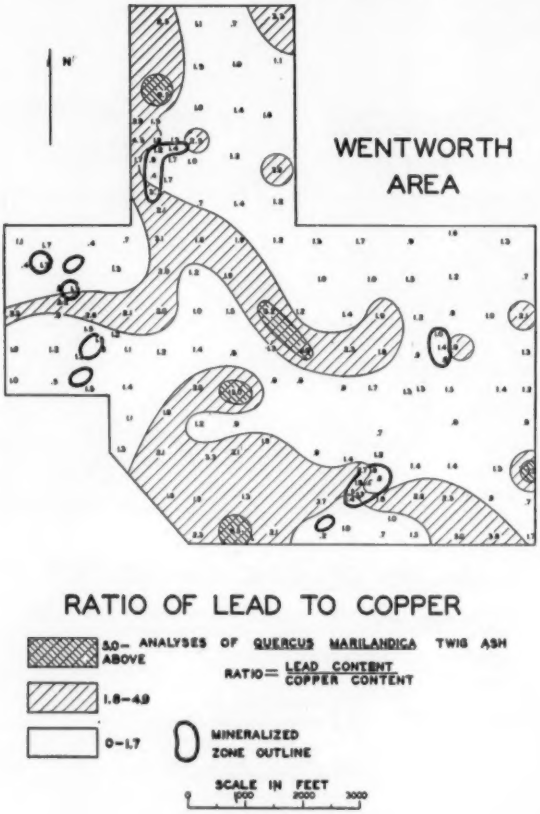


FIG. 7.

village of Wentworth. The area contains small, erratically distributed mineralized zones, of moderate grade, that lie at depths of about 70 feet. The outlines of the mineralized zones, inferred from drilling data of the Eagle-Picher Mining and Smelting Company, are illustrated in Figures 2 to 11. There are probably other mineralized zones, the presence of which remains unknown for lack of further exploration. The Wentworth area occurs in the "Boone" limestone,

which weathers to a cherty, red-clay soil. The area is covered with forests and fields. The topographic relief is slight. There are no tailings piles within the area, although there are a number of small tailings piles on the southwest outskirts of the area. Various trees were sampled over the mineralized zones and

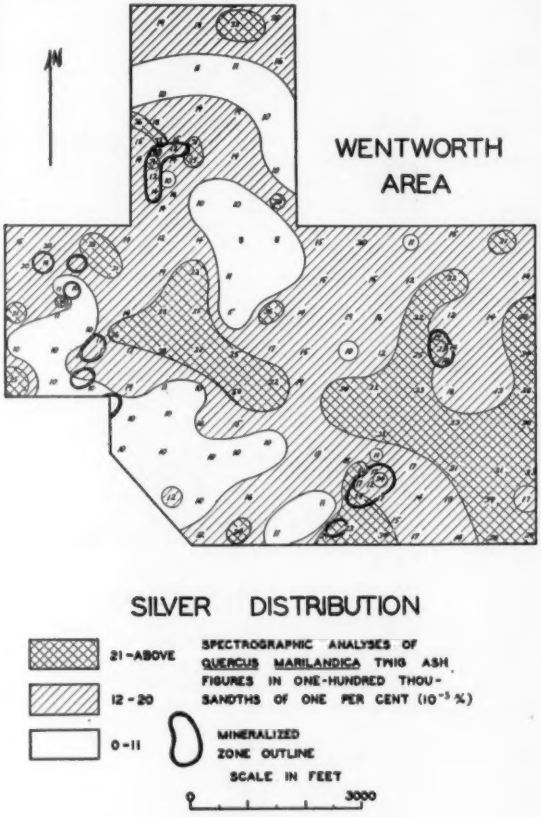


FIG. 8.

twigs samples of the blackjack oak, *Quercus marilandica,* were gathered on a grid that embraced the entire area.

The Dombroski area, lying in Barry County, Missouri, provided samples of trees and herbaceous plants. A "sheet ground" deposit, of moderate grade, lies at a depth of about 90 feet. The "Boone" limestone is exposed here, as it is throughout the eastern part of the Tri-State district. A moderate sized tailings pile, lying about a half mile distant, is the only vestige of mining activity within

a number of miles, indicating slight possibility of contamination. The topography is hilly, and the surface is covered with fields and patches of trees.

The Sullivan area, in Ottawa County, Oklahoma, served as a source of various prairie plants, which were collected over the mineralized zones (Fig. 12).

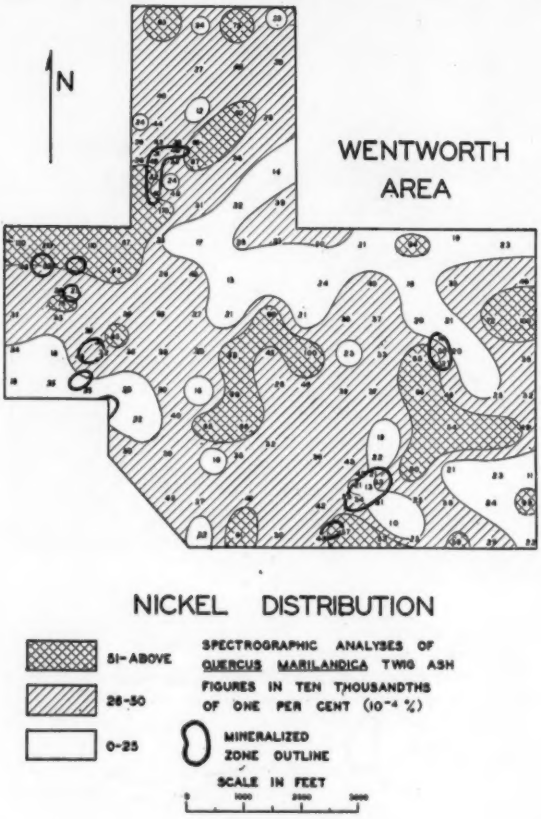


FIG. 9.

Over the uniform flat prairie, samples of the gayfeather, *Liatris pcynostachya*, were gathered on a grid. Existing information indicates the presence of a small zone of low-grade mineralization, lying at a depth of about 75 feet. If more drilling information were available, the outlines, as inferred, might be altered or extended. There is a covering of post-"Boone" shale, possibly 10 or 15 feet thick, creating soil of a somewhat different nature than in the exposed areas of the "Boone."

Non-mineralized Areas.—For purposes of contrast, four widely spaced localities, presumably barren of mineralization, were chosen to provide samples of the same types and species of plants as were collected above mineralized zones. These are the Wheaton, Rocky Comfort, Neosho and Seneca barren areas, as

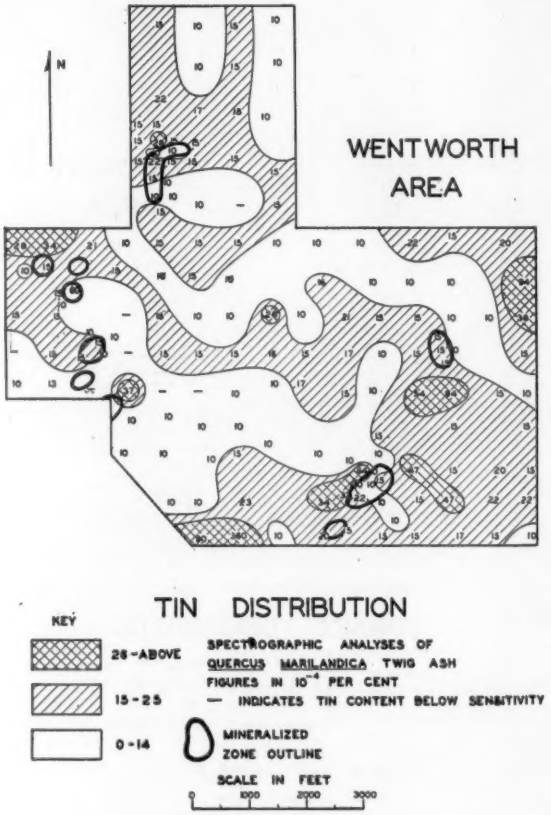


FIG. 10.

shown in Figure 1. They have been presumed to be barren of mineralization because of their distance of five miles or more from the nearest mining site. None have been drilled to the author's knowledge. All are in the "Boone" limestone and have soil and ecological conditions essentially equivalent to those of the Wentworth and Dombroski areas.

SAMPLING.

In the early stages of this investigation, plant samples were collected either immediately above mineralized zones or in barren areas lying some miles distant from the mineralized zones. The samples were analyzed and the metal contents contrasted. Later in the work, it was decided to investigate the more

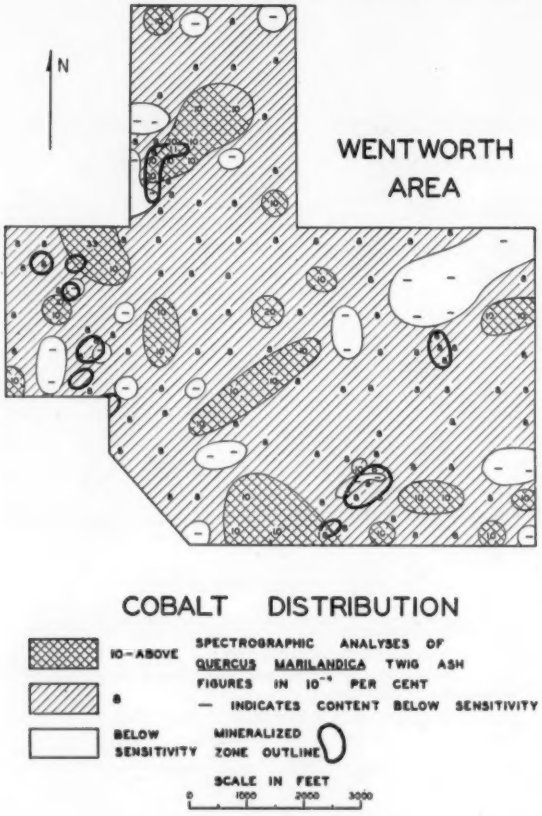


FIG. 11.

subtle changes in metal concentration in plants growing at varying distances from mineralized zones. A grid system of collection was employed, enabling the distribution of metals in a particular species to be plotted and contrasted with the underlying mineralized zones. By judicious location of samples, the danger of possible contamination from prospecting dumps and other sources has been minimized. Samples of *Quercus marilandica* were collected about

one-eighth mile apart in the Wentworth area, although the spacing was closer in key places. The interval employed conformed to the pattern of fields, forest and hedgerows. In the Sullivan area, samples of the blue-flowered gayfeather, *Liatris pcynostachya,* were collected at intervals of about 200 feet.

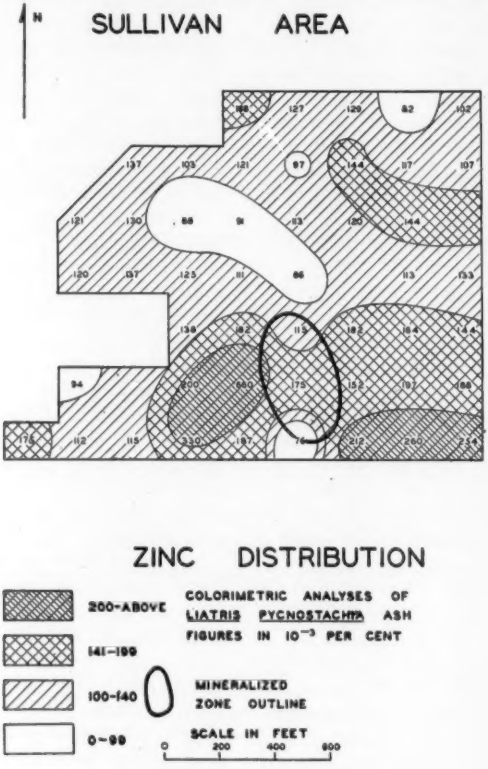


FIG. 12.

Samples were cut with pruning shears. The entire upper portion of the prairie plants was gathered, the cut being made a foot or more above the ground, if possible, to avoid soil splash. In sampling trees, leaves and twigs were cut from various branches. In order to obtain the most representative samples, cuttings were generally made from several trees of the same species near the same location. It was not possible to collect samples from trees of uniform age or size. However, twig cuttings were of a standard size, about one-fourth inch in diameter. The samples, weighing about one pound at the time of collection, were placed in mesh bags which were in turn sealed in paper bags to prevent the admission of dust in transportation.

After being air-dried for a month or more, the samples were ground in a hammermill and the ground material stored in pint cartons until ashing. Ashing was performed in porcelain evaporating dishes heated to a dull red over bunsen burners. The ash was stirred until it was a uniform gray color and no glowing carbon particles remained, requiring about 15 minutes. No precautions were taken to prevent loss of volatiles; it being assumed that losses of heavy metals would be more or less uniform from sample to sample, since each was subjected to the same conditions. The ash was stored in tightly corked glass vials to prevent absorption of water.

Analyses.—All samples were analyzed for zinc and some samples for lead, tin, copper, nickel, cobalt and silver. All of these metals were considered to be of possible biogeochemical importance. Zinc was determined by means of a colorimetric method using dithizone, as described by Sandell [4] and modified from Reichen and Lakin.[5] Copper was determined using potassium ethyl xanthate as a colorimetric reagent.[6] The spectrographic analyses, in which lead, nickel, tin, silver and cobalt were jointly determined, were performed at the Research Laboratories of the Eagle-Picher Company, at Joplin. Mr. James S. Bryson, of the laboratory staff, devised the spectrographic technique.

Repeated analyses upon particular samples indicated a low standard deviation for zinc, with lesser degrees of reproducibility for the other metals. The standard deviations are $\pm 2\%$ for zinc, $\pm 10\%$ for lead, $\pm 11\%$ for copper, $\pm 16\%$ for nickel, $\pm 16\%$ for tin and $\pm 26\%$ for silver. Cobalt showed still poorer reproducibility. Single determinations were made of the majority of samples; hence all of the figures expressing metal content are subject to moderate degrees of error. However, the interpretation of analyses is not considered to be invalidated by the inherent analytical errors, as the presentation of data and the conclusions are based on many analyses. Metal concentrations have been expressed as percentages and as parts per million of ash.

Contamination.—In studies of the effect of dust as a contaminating agent, it was found that samples laden with dust would show a considerably higher concentration of zinc and lead, but that, in the majority of cases, samples with a light coating of dust showed negligibly higher zinc and lead concentrations. Furthermore, the collections were made during periods of frequent rains, which removed much of the dust that might have settled on the plants. The samples, except those especially gathered for their dust coating, gave the appearance of being dust-free. Therefore, it has been assumed that the contaminating influence of small amounts of dust is negligible.

Plants growing about the edges of tailings piles are known to show abnormally large amounts of zinc. Yet, it is to be noted that samples of *Quercus marilandica* gathered at the southwestern edge of the Wentworth area, about 500 feet from a group of small tailings piles, did not show larger amounts of zinc or any other metal than did plants collected from the remainder of the

[4] Sandell, E. B., Colorimetric determination of traces of metals, pp. 449–460, Interscience Publishers, 1944.

[5] Reichen, Laura E., and Lakin, H. W., Field method for the determination of zinc in plants: U. S. Geol. Survey Circ. 41, 4 pages, 1949.

[6] Scott, W. W., Scott's standard methods of analysis, pp. 376–377, Van Nostrand Co., New York, 1939.

Wentworth area. Similarly, the prairie plants of the Sullivan area, which lies within a mile of many large tailings piles, showed zinc concentrations essentially equivalent to those in corresponding prairie plants gathered in the Dombroski and Wentworth areas, which have far fewer tailings piles on their outskirts.

In sampling, care was always taken to avoid collections near rock dumps, drill cuttings thrown on the ground, and other possible sources of contamination. Consequently, contamination is considered by the author probably to be negligible on the whole, although it may exist in a few samples.

RESULTS.

Two methods of presentation of data have been employed: (I) The analyses, expressed in parts per million (ppm) of ash, of various species (samples consisting of leaves, twigs, or entire plant except for roots) have been tabulated in three categories: (a) Analyses of various plants collected above mineralized zones; (b) analyses of various plants collected in areas presumably barren of mineralization; and (c) analyses of twigs of *Quercus marilandica* gathered throughout the entire Wentworth area in which the samples collected above or

TABLE 1.

HEAVY METAL ANALYSES OF *Quercus marilandica* TWIGS.

Comparison of analyses of *Quercus marilandica* twig samples from the Wentworth area with samples from the Rocky Comfort, Neosho and Seneca barren areas.

Figures are parts per million of ash. The average concentration is recorded.

	A	B	C	D
	Samples above and marginal (zone of 300 feet width) to known mineral zones, Wentworth area 56 samples	Samples not above or marginal to mineral zones of Wentworth area 101 samples	All samples collected in Wentworth area 157 samples	Samples from Rocky Comfort, Neosho and Seneca barren areas 23 samples
Zinc	1100	850	940	660
Copper	220	210	210	220
Lead	310	340	330	340
Tin	18	17	17	16
Nickel	45	37	40	45
Cobalt	8	8	8	9
Silver	1.8	1.8	1.8	2.5

near mineralized zones were contrasted with those from the remaining barren portions of the area. (II) For the Wentworth and Sullivan areas, where samples were gathered on a grid system, metal concentrations have been plotted on maps and concentrations between various specified limits have been shown by cross-hatching in Figures 2 to 12.

Of the seven metals listed in Table 1, only zinc shows significant variations. The average zinc concentration of the samples collected above and marginal to the mineralized zones (group A) is greater than in the other groups to the following extent: 29 percent greater than the average of samples not above or marginal to mineralized zones (B) and 67 percent greater than the average of

samples from areas presumed totally barren of mineralization (D). The average zinc concentration of samples gathered throughout the entire Wentworth area (C) is about 42 percent greater than the average of the barren area samples (D).

These data indicate a probable relationship between zinc concentration in *Quercus marilandica* and the proximity of mineralized zones. It has been

TABLE 2.

ZINC ANALYSES OF VARIOUS TREE SPECIES.

Tabulation of zinc analyses of leaves and twigs of various tree species. Samples collected above or near mineralized zones have been contrasted with samples from barren areas.

Figures are parts per million zinc of ash. Number of samples analyzed for average concentration is contained in parentheses.

Plants collected above or near mineralized areas are from the Wentworth and Dombroski areas. The Wheaton, Neosho, Rocky Comfort and Seneca barren areas supplied the "barren area" samples.

	Mineralized zones		Barren areas	
	Leaves	Twigs	Leaves	Twigs
Acer saccharinum L. Soft Maple	(2) 1600	(3) 1900	(1) 2100	(3) 1400
Carya cordiformis (Wang.) Koch. Pignut	(1) 1800		(1) 850	
Carya ovalis obvalis (Marsh) Sarg.	(3) 3000	(4) 2300	(1) 400	(1) 900
Carya ovata (Mill) K. Koch. Hickory	(2) 2800	(2) 2200	(2) 1400	(1) 1800
Cornus florida L. Flowering Dogwood		(2) 1700		(1) 400
Juglans nigra L. Black Walnut	(2) 2200	(2) 1200	(1) 600	(1) 400
Juniperus virginiana L. Red Cedar	(4) 1250	(3) 1250	(1) 600	(1) 600
Maclura pomifera (Raf.) C. K. Schneid. Osage Orange	(2) 800	(2) 800	(2) 800	(1) 600
Platanus occidentalis L. Sycamore	(3) 400	(2) 600	(3) 500	(3) 300
Prunus serotina Ehrh. Black Cherry	(1) 2200		(1) 900	
Quercus alba L. White Oak	(4) 500	(3) 400	(2) 500	(2) 2800
Quercus borealis maxima (Marshe.) Ashe. Red Oak	(1) 500	(1) 500	(1) 900	(1) 350
Quercus macrocarpa Michx. Bur Oak	(2) 500	(1) 300	(1) 500	(1) 800
Quercus marilandica Münch. Blackjack Oak	(5) 1500	(63) 1110	(1) 600	(24) 660
Quercus muhlenbergii Engelm.	(1) 800	(1) 700	(1) 450	(1) 400
Quercus palustris Münch. Pin Oak	(1) 600	(1) 300	(1) 1700	(1) 500
Quercus stellata Wang. Post Oak	(6) 850	(3) 1100	(1) 700	(1) 600
Quercus velutina Lam. Black Oak	(5) 1200	(3) 1400	(2) 1000	(3) 600
Rhus copallina L. Sumac	(5) 600	(2) 600	(3) 600	(3) 800
Robinia pseudoacacia L. Black Locust	(1) 500		(3) 1050	
Sassafras albidum (Nutt.) Nees	(3) 850	(3) 850	(3) 1050	(3) 1100
Ulmus alata Michx. Winged Elm		(1) 800		(2) 500
Ulmus americana L. American Elm	(4) 1000	(3) 800	(3) 1250	(4) 800
Ulmus fulva Michx. Slippery Elm	(1) 600	(1) 400	(1) 500	(2) 400
Average parts per million zinc of ash for all species	1190	1000	860	800

shown that contamination by dust is probably negligible, and care was taken to prevent contamination from rock dumps and other sources. It is believed that the distribution of zinc is a reflection of natural conditions and that the higher average zinc concentration in twigs of *Quercus marilandica* growing near mineralized zones is most probably attributable to the presence of much greater amounts of zinc in the subsurface.

Referring to Table 2, the average zinc concentration for all tree species is about 28 percent greater for leaves and 25 percent greater for twigs in samples collected above mineralized zones than in samples collected in areas presumably

barren of mineralization. The higher concentrations above mineralized zones are believed to be a reflection of the presence of the mineralization.

The individual species contained in Table 2 show wide variations in zinc concentration of leaves and twigs in samples both from above mineralization and from barren areas. *Juniperus virginiana,* for instance, shows an average of 1,250 ppm for both leaves and twigs in samples from above mineralized zones and an average of 600 ppm for both needles and twigs in the samples from barren areas. *Quercus alba,* on the other hand, contained an average of 500 ppm in the leaf samples growing above mineralization and also 500 ppm in the

TABLE 3.

ZINC ANALYSES OF GRASSES AND HERBACEOUS PLANTS.

Tabulation of zinc analyses of grasses and herbaceous plants in which those collected over mineralized zones are contrasted with those from barren areas.

Figures are parts per million of ash. The number of samples analyzed in determining the average concentration is contained in parentheses.

Samples consist of entire plant with exception of roots and lowei portion of stem.

Samples from above mineralized zones were collected in the Wentworth, Dombroski and Sullivan areas. Samples from barren areas are from Seneca, Wheaton and Neosho areas.

	Mineralized zones	Barren areas
Ambrosia coronopifolia T. & G. Ragweed	(1) 1800	(3) 1400
Ambrosia elatior L. Ragweed	(1) 1700	(1) 1800
Ambrosia trifida L. Giant Ragweed	(1) 5000	(3) 1500
Andropogon furcatus Muhl. Big Bluestem	(3) 700	(2) 500
Andropogon scoparius Michx. Little Bluestem	(2) 500	(1) 450
Apocynum sibiricum Jacq. Dogbane	(1) 1000	(1) 450
Gnaphalium obtusifolium L. Cudweed	(2) 2500	(1) 1500
Helianthus mollis Lam. Sunflower	(2) 2100	(1) 800
Liatris aspera	(2) 2200	(1) 800
Desmodium sessilifolium (Torr.) T. & G.	(2) 1000	(1) 1200
Phytolacca decandra L. Pokeweed	(1) 600	(1) 2200
Salvia pitcheri Torr.	(1) 1000	(1) 1500
Sorghastrum nutans (L.) Nash. Indian Grass	(2) 800	(1) 600
Symphoricarpos orbiculatus Moench. Buckbrush	(4) 1000	(4) 900
Tridens flavus	(3) 1200	(2) 2100
Vernonia interior Small. Ironweed	(2) 1200	(2) 1100
Average parts per million zinc of ash for all species	1520	1170

leaf samples from barren areas. The twig samples, however, contained an average of 400 ppm in samples collected above mineralization and an average of 2,800 ppm in barren areas. It is obvious that individual samples, of leaves or twigs, growing in any locality can show great variations in zinc concentration. Therefore, conclusions concerning zinc concentrations always have been based on the average of many samples.

Referring to Table 3, the average zinc concentration for all species of grasses and herbaceous plants collected above mineralized zones is about 30 percent greater than the average zinc concentration for all samples from the various barren areas. Thus, again, there appears to be a direct relationship between the zinc concentration of these plants and the proximity to zones of mineralization.

The distribution of zinc shown in Figure 2, as plotted from analyses of *Quercus marilandica* twigs collected in the Wentworth area, shows moderate

correlation with known mineralized zones. There are a number of "highs" of zinc distribution, some of which partially coincide with known mineralized zones. It must be borne in mind that the outlines of mineralization, as shown, are those deduced from drilling data. The likelihood is great that there are other unknown mineralized zones. If more drilling information were at hand, the outlines might be altered or extended. Some of the "highs," as plotted from plant analyses, may thus actually lie partially or wholly above undiscovered zones of mineralization.

If the distribution of zinc is considered in those samples collected immediately above the mineralized zones as well as in the samples collected within a margin 300 feet beyond the surface projection of the mineralized zones, it will be seen that there is a better correlation between zinc concentration in plants and subsurface mineralization. It is shown, in Table 1, that the average zinc concentration of all samples of *Quercus marilandica* above or marginal to mineralized zones is about 29 percent greater than the average concentration of all remaining samples of the Wentworth area. Thus, the degree of correlation is shown somewhat better statistically than graphically.

Drainage and topography appear to have had no bearing upon the distribution of zinc in plant samples. Contamination from the small tailings piles immediately to the southwest of the area appears negligible or non-existent, for samples collected nearest the tailings piles are not, on the whole, higher in zinc content than those throughout the rest of the area.

In conclusion, it may be stated that in detail the plot of zinc distribution, shown in Figure 2, does not correspond particularly well with the extent of known mineralization. If the influence of mineralization is considered to extend beyond the boundaries of the mineralized zones, the correlation is somewhat better.

As shown in Figure 3, the distribution of lead is erratic and, apparently, is governed by causes other than underlying mineralization. There are definite trends in the distribution pattern, some of which show a similarity to trends in the distribution of zinc, tin and other metals. The drainage and topography seem not to have governed lead distribution in the samples. Contamination from tailings piles lying immediately to the southwest of the Wentworth area has apparently been negligible, for samples collected nearest the tailings piles reveal relatively low concentration of lead. The pattern of lead distribution does not appear to give promise as a guide in prospecting.

Referring to Figure 4, the distribution of copper appears to be largely independent of known mineralization. There are some copper "highs" occupying the same positions as do "highs" of zinc, lead, nickel and tin, suggesting that factors affecting the distribution in plants of one metal sometimes have a similar effect upon other metals. Again, topography and drainage seem to have had no effect. Contamination also appears improbable.

The distribution of the ratio of zinc to lead (Fig. 5) shows some relation to known mineralization. There is a large irregular shaped area of high zinc-lead ratio lying about the westernmost group of mineralized zones and an irregular "high" covering the northernmost mineralized zone and extending to the edge of the Wentworth area. These "highs" exhibit about the same degree of correlation with mineralized zones as does the distribution of zinc. Topography

and drainage seem not to have influenced the distribution of the ratio of zinc to lead.

The distribution of the ratio of zinc to copper and of lead to copper (Figs. 6, 7) shows little apparent correlation with mineralized zones. The distribution of silver, nickel, tin and cobalt (Figs. 8, 9, 10, 11) similarly shows little apparent correlation with mineralized zones.

The distribution of zinc in samples of *Liatris pcynostachya* in the Sullivan area (Fig. 12) shows some correlation with known mineralization. There are two "highs," lying to the east and to the west of the mineralized zone. While not coinciding with the inferred outline of the zone, these "highs" are, nevertheless, near enough to be a possible reflection of mineralization. Furthermore, the scanty drilling information for the Sullivan area has not eliminated the possibility that mineralization may extend beyond the present known outlines. Drainage apparently has not influenced zinc distribution. The small brook that runs in a meandering northward course across the west-central part of the area crosses regions of high zinc concentration as well as regions of low concentration. The southern edge of the area is bounded by a road surfaced with mill tailings, yet several samples gathered near the road exhibited low concentrations of zinc, indicating a lack of contamination from the road.

CONCLUSIONS.

This investigation in the Tri-State district has shown that biogeochemical anomalies exist, judging from analyses of large numbers of plant samples. Zinc has been found in higher average concentrations in plants growing above or near shallow mineralized zones (less than 100 feet in depth). Precautions were taken to avoid sources of contamination, and it is thought that contamination from dust or other causes is negligible. It is therefore probable that the average metal concentrations recorded in a large number of samples is a function of natural conditions. The presence of underlying mineralized zones appears to be the probable cause of greater amounts of zinc in the plants growing above or near such zones.

The analyses of various grasses and herbaceous plants, as well as the leaves and twigs of trees, indicate that all plants show great variation in metal concentration. It appears that considerations of abundance and wide distribution govern the choice of plants to be analyzed in any biogeochemical survey of this district. Both leaves and twigs seem to be suitable, although leaves have shown a higher average zinc concentration. Uniformity of size and age, in samples of a species, is desirable though, apparently, not essential.

Biogeochemical methods thus appear to offer promise as aids in prospecting in the Tri-State district, especially in areas where the "Boone" limestone is exposed. In all cases, conclusions as to anomalous zinc concentrations should be based on the average of the analyses of large numbers of samples, preferably of a common plant. Anomalies thus revealed may give an indication of the occurrence of concealed mineralization.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF KANSAS,
March 26, 1950.

THE APPRAISAL OF ORE RESERVES AT A JAPANESE COPPER MINE.[1]

JOHN J. COLLINS.[2]

ABSTRACT.

Estimates of ore reserves at major Japanese metal mines seem, at first glance, to be readily understandable to American engineers and geologists. Close scrutiny, however, generally reveals unexpected features at each mine.

For example, the Hitachi copper mine formerly segregated its developed ore reserve into *positive* and *probable* on the basis of the possibility of high-grade and low-grade production from individual stopes.

Tests were made by the writer at Hitachi on the accuracy of the original reserve estimates of a few ore blocks by comparing those figures with the final production data. The results suggest that the average reserve estimate of positive ore may be accurate within 20 percent, plus or minus.

A ten-year supply of proved ore at the big mines is not unusual; hence Hitachi is not much concerned with the additional categories of *probable* and *possible* ore, unless the positive ore has become inaccessible because of caving of the workings. For the sake of comprehensiveness, however, the writer studied the assay maps and stope maps in collaboration with the mine management and estimated tonnages of probable and possible ore, qualified by lower reliability ratings. Exploration prospects also were described in actual figures, subject to a variation of plus-or-minus 75 percent.

INTRODUCTION.

ONE of the many phases of the Allied Occupation of Japan was the appraisal of the mineral resources of that formerly secretive country. This report, prepared in February 1946, on the Hitachi Mine of the Nippon Mining Company, is a part of the first detailed effort by members of the Allied Forces to acquire and present the facts of the mineral-resource position of Japan. Fortunately, the mining companies were entirely cooperative.

Hitachi merits detailed analysis because it is the third largest non-ferrous metal mine in Japan, having produced 17,000,000 metric tons of ore, entirely from underground workings, with an average grade of 1.6 percent copper. Later examination of other major mines revealed that this description of ore reserve calculations is a fair example of the variety of methods practiced in Japan. No standard procedure was observed and a foreigner should take nothing for granted.

The author's methods herein described are the basis for the national totals of copper reserves appearing in "Copper in Japan."[3] The time available did

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Geologist, U. S. Geological Survey, formerly assigned to the Natural Resources Section, General Headquarters, Supreme Commander for the Allied Powers, Tokyo, Japan, by arrangement with the Office of the Chief of Engineers, U. S. Army.

[3] Published as Report 106, Natural Resources Section, GHQ, SCAP, 1948, and reprinted by U. S. Bureau of Mines as Mineral Trade Notes, Special Supplement No. 26, May 1948.

not allow any original field work; the objective was simply an appraisal of existing information and procedures.

THE ORE OCCURRENCE.

The ore bodies of the Hitachi Mine, Ibaraki Prefecture, Japan, consist primarily of pyrite with enough chalcopyrite to bring the grade to 1 to 3 percent copper. Common accessory minerals are pyrrhotite, magnetite, and sphalerite, but the zinc content rarely exceeds 1 or 2 percent. Gold and silver values combined amount to less than one dollar per ton.

This massive sulfide ore has sharp boundaries with the waste rock, but layers of barren rock are commonly included in the ore bodies. The ore bodies are generally lenticular in shape but vary in size. The largest is of the order of magnitude of a million tons. They are arranged en echelon over a distance of a mile and have been developed to a vertical depth of half a mile.

The host rock is schist of varied composition; four main types are recognized: biotite, chlorite, sericite, and anthophyllite schist. The associated igneous rock is granodiorite that occurs as a body of batholithic size.

RESERVE CALCULATIONS.

Channel Samples.—Channel sampling is a regular procedure only on the main levels. Occasionally stopes are sampled, if a foreman wants to check mill head assays, but raises and winzes are rarely sampled. This procedure means that usually ore estimates are based on data from only the top and bottom of an ore block. Levels are spaced at 50 meter intervals.

The samples are cut in the roof at right angles to the strike of the ore and are roughly three centimeters wide by three centimeters deep (a little over one inch by one inch and nearly two pounds per linear foot). Samples are spaced at intervals of 4.5 meters (15 feet).

The full width of a drift is cut as one sample, but samples are collected only of the sulfide layers. Waste rock is not sampled even though it commonly occurs between layers of ore and would have to be mined along with the ore. The result is that the underground samples indicate a grade of ore higher than can be mined. The mine superintendent uses them only as part indicators of stoping possibilities.

Car Samples.—All cars hoisted from the mine are sampled and weighed before they go into the mill. Each car holds approximately one metric ton of ore. All the car samples from each stope or block of ore are combined for 5-day periods before being sent to the assay office. These composite samples are assayed only for copper and the results are recorded for each working place.

Plotting and Calculating Reserves.—The channel sample data are carefully plotted in the metric system, on level maps on a scale of 1 : 600 (one inch equals 50 feet). The assays are shown on these maps and the ore zone is outlined in red but no stoping widths appear. In order to determine expectable stoping widths, the management experimented with a graph of ore widths plus waste widths. Horizontal measurements were used. This diagram is based on several hundred measurements and is probably reliable in a general way, but of

course it cannot take into account local variations in the ore occurrence. These variations could be critical in the recognition of the marginal ore as distinguished from ore and waste. In actual practice the expectable average width of an ore block is obtained by averaging the full width of the development drifts above and below the block. In other words, the development drifts, despite the usual overbreaking, are used as the measure of stoping widths.

Average grades of ore blocks are assigned by the mine superintendent by comparing the adjacent production records with the averages of adjacent channel samples.

Measurements in the vertical plane are taken from vertical longitudinal sections that are best suited for the representation of Hitachi's steeply dipping deposits. Little ore is included in the reserve unless it has been developed by levels and raises to the point where stoping could begin with little additional work.

Tonnages and grades are calculated in the conventional manner with the following notable features. Though variations in the specific gravity of the ore are known to range from 3.5 to 4.5, the figure 4.0 is used for ore calculations. In the metric system this conveniently means four metric tons to the cubic meter of ore. The figure 2.6 is used as the specific gravity for waste. The thickness cut-off for reserves is 20 centimeters of ore regardless of how rich the ore may be. Where copper is lower than 0.5 percent, a minimum of 30 percent sulfur is required to constitute pyrite ore. Ordinarily the proportion is about one percent copper to 20 percent sulfur in the ore. Minimum stoping width in the ore reserve is 2.1 meters (6.5 feet). Moisture content of the ore averages 5 percent but all calculations are on a dry basis.

Accuracy.—Although the grade of mine production has been very close to the grade of reserves for the last 16 years, the author requested that specific checks be made on the reserve data. With the usual ready cooperation of the mine management, a few ore blocks were chosen for study on the basis of completeness of mining in the period 1930–1945.

The comparison of production with certain reserve estimates revealed that actual production averages $\frac{1}{5}$ greater in tonnage, $\frac{1}{20}$ lower in grade, and $\frac{1}{6}$ higher in total copper content, than the figures in the estimates. The greatest error in a single block resulted in production being $\frac{7}{10}$ greater in tonnage, $\frac{1}{5}$ lower in grade, and $\frac{2}{5}$ higher in copper content, as compared with the reserve estimate. All but one block produced more crude ore of lower grade than the estimate; without exception they all yielded more copper than was estimated. The details are shown in Tables 1 and 2.

This check on the accuracy of the system covers only a few ore blocks that have been almost completely mined. Some of the blocks that have not been completely mined may have had an unexpected amount of ore that was poorer than the estimates. These opposite possibilities may balance, but an exact determination is impossible, as the records vary with the opinions of the mine superintendent as he revised the figures each year in conformance with mining results in and around each block.

For general purposes it seems sufficient simply to recognize the probable limits of accuracy of the estimates. A real determination of their accuracy

TABLE 1.

SOME CHECKS ON THE ACCURACY OF FORMER ORE ESTIMATES, AT THE HITACHI COPPER MINE (METRIC TONS).

Ore shoot, ore blocks, by levels	Date	Earliest estimates			Date	Latest production records		
		Tons ore	% Cu	Copper content		Tons ore	% Cu	Copper content
Irishiken	Est. 1932	55,200	1.59	876.6				
250–300	Mined	17,700	1.57	278.6				
levels	Total Block	72,900	1.58	1155.2	Total Mined	77,041	1.51	1165
Kammine								
No. 6	Est. 1939	18,200	0.90	163.8	Mined to 1945	25,775	0.77	197.7
150–200	Mined	1,100	0.96	10.6	1945 Reserve	4,900	0.78	38.2
levels	Total Block	19,300	0.90	174.4	Total Ore	30,675	0.77	235.2
Takasuzu								
No. 6	Est. 1938	48,400	1.00	484.0	Mined to 1945	49,251	1.36	667.4
90–120 levels	Mined	8,584	1.48	127.2	1945 Reserve	800	1.20	9.6
	Total Block	56,984	1.07	611.2	Total Ore	50,051	1.35	677.0
Takasuzu	Est. 1932	37,500	1.41	529.9	Mined to 1945	203,900	1.71	3495.4
60–90 levels	Mined	135,900	1.89	2570.8	1945 Reserve	2,700	1.39	37.6
	Total Block	173,400	1.79	3100.7	Total Ore	206,600	1.71	3533.0
Hanko No. 2	Est. 1940	56,500	1.61	909.3	Mined to 1945	95,416	1.36	1297.2
150–200	Mined	8,700	1.89	163.7	1945 Reserve	14,800	1.30	192.0
levels	Total Block	65,200	1.65	1073.0	Total Ore	110,216	1.35	1489.2
Totals and average grade		387,784	1.57	6114.5		474,583	1.50	7100.1

TABLE 2.

COMPARISON OF PRODUCTION RECORDS WITH THE EARLIEST ESTIMATES DERIVED FROM TABLE 1. Production is plus or minus the estimates.

Ore shoot, ore blocks, by levels	Difference in actual figures			Difference in percent		
	Tons ore	Copper grade %	Copper content	Tons ore	Copper grade %	Copper content
Irishiken 250–300	+4,141	−.07	+9.8	+6	−4	+1
Kammine No. 6 150–200	+11,375	−0.13	+61.5	+59	−14	+35
Takasuzu No. 6 90–120	−6,933	+.28	+65.8	−12	+26	+11
Takasuzu No. 1 60–90	+33,200	−.08	+432.3	+19	−4.5	+14
Hanko No. 2 150–200	+45,016	−.30	+416.2	+69	−18	+39
Totals	+86,799	−.08	+985.6	+22	−5	+16

would require considerable sampling, assaying, and calculation. As a result of this preliminary investigation the company's estimates of proved ore, including both high-grade and low-grade, are considered to have a reliability rating of plus-or-minus 20 percent for the ore they include.

Classification of Ore Blocks.—It has been traditional at the Hitachi Mine for the management to divide all ore blocks into what they call *positive* and *probable* classes. The positive-probable distinction is based not so much on the degree of development nor on the closeness of sampling, but chiefly on an arbitrary opinion as to what grades of ore could be produced from each block. Actually the mining record shows that the grade of ore produced has been much closer to the combined *positive-probable* grade than to either component. Following are the arithmetical averages, in percentage of Cu, for the period 1930–1945:

1. Grade of positive ore reserve	1.47
2. Grade of probable ore reserve	1.01
3. Grade of combined reserves	1.21
4. Grade of ore produced	1.24

This special application of the terms *positive* and *probable* reveals that they might be interpreted to mean *high-grade* and *low-grade* ore. Furthermore, the distinction is not concerned with the degree of development, as seven-eighths of the ore in the reserve could be classed as *developed* for mining. Apparently this Hitachi usage of *positive* and *probable* is a hypothetical classification of the mine's possibilities for higher- or lower-grade production.

A new and additional classification, started in 1945 by Mr. Nomura, Superintendent of the Mine and Mill, subdivides the reserves by accessibility and profitability into A, B, and C groups. The A, B, C classification has resulted from the fact that many developed blocks of ore have become relatively inaccessible. The reserve of developed ore has averaged about a 10-year supply, as a tradition of the mine. As a result, many haulageways sloughed, squeezed, or caved before the ore was needed. The cost of reopening the working places, in many cases, has become prohibitive, and inaccessible low-grade ore now comprises two-thirds of the total.

To illustrate this situation Mr. Nomura started classifying blocks by their accessibility and probable net value after re-opening and mining. Class A blocks are available for immediate mining and have the highest net value. Class B blocks require some re-opening, repairs, and their net value is about half that of Class A. Class C ore requires considerable transportation expense, repair work, or more development work, which puts this ore in a category of an unprofitable reserve under present conditions. Mining costs of Class C blocks might be double of the costs of Class A blocks.

Probable and Possible Ore.—In addition to the company's listed reserves a comprehensive estimate would need to consider the additional ore that is only partly developed or incompletely explored. Inspection of the stope maps and the assay maps in collaboration with the mine management suggests that a great deal more ore can be predicted, but with less reliability.

If an accuracy of plus-or-minus 35 percent is suitable for *probable* ore in the American sense, then it seemed reasonable to the author to list half as much tonnage in the probable class as the company had already developed in the proved class. Moreover, if the class of *possible* ore can be viewed with an accuracy of plus-or-minus 50 percent, then an additional amount equal to the probable ore could be listed in this category.

Total Reserves.—The following tabulation is thought to be a comprehensive, though generalized, summation of the reserves in the known ore bodies of the Hitachi Mine:

Proved ore	± 20%:	6,000,000	metric tons averaging	1.1%	copper
Probable ore	± 35%:	3,000,000	metric tons averaging	1.1%	copper
Possible	± 50%:	3,000,000	metric tons averaging	1.1%	copper
Total	± 30%:	12,000,000	metric tons averaging	1.1%	copper

The proved ore has been divided further as:

Class A, profitable:	1,100,000 tons,	1.3% Cu,	14,300	tons copper
Class B, marginal:	1,000,000 tons,	1.3% Cu,	13,000	tons copper
Class C, sub-marginal:	3,900,000 tons,	1.0% Cu,	39,000	tons copper
Total:	6,000,000 tons,	1.1% Cu,	66,000	tons copper

Exploration Prospects.—The foregoing tabulation covers only the *known ore bodies.* The property, which is extensive, has a number of mineralized outcrops and underground exposures that are too low grade or too small to be classed as reserves. However, they do suggest that the known ore bodies may not be the only ones on the property.

The structural geology of the district has not been mapped in detail, but the area seems to have possibilities for the discovery of new ore bodies. Ore may exist not only where it crops out in commercial bodies, but also in concealed sites where its presence can be inferred only indirectly on the basis of favorable structural, mineralogic, and petrologic conditions.

Prediction of the reserves contained in undiscovered ore deposits is obviously speculative and the odds are against any single exploration project being successful. Nevertheless the Hitachi area is extensively mineralized and has an impressive production record of 17,000,000 metric tons averaging 1.6 percent copper. If an accuracy variation of plus-or-minus 75 percent is allowed, it seems that 6,000,000 tons of 1.6 percent copper ore may remain to be discovered in new ore bodies. When this will be discovered probably depends on the application of new techniques spurred by adequate commercial incentive.

Submarginal Ore.—The exposures of submarginal ore suggest that there are larger tonnages of low-grade material that conceivably could be of future interest, but the task of compiling and analyzing such data seemed beyond the scope of this investigation.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
April 1, 1950.

MASSIVE LEUCOXENE IN ADIRONDACK TITANIUM DEPOSIT.[1]

E. P. WHEELER, 2ND.

ABSTRACT.

A series of minerals from hornblende to chlorite have filled cavities in anorthosite adjacent to a titaniferous magnetite deposit and associated with faulting. Ilmenite crystals formed early in the series and their outer portions were subsequently altered to leucoxene of variable composition for a thickness of a centimeter.

GENERAL DESCRIPTION OF DEPOSIT.

LEUCOXENE as massive pseudomorphs after ilmenite crystals occurs in the anorthosite associated with a titaniferous magnetite body on the east shore of Lake Sanford in Essex County, New York. The ore body has been described in some detail by R. C. Stephenson.[2]

The largest specimens of leucoxene were found in the filling of an open cavity in anorthosite at the contact with massive titaniferous magnetite. The following minerals, approximately in the order of decreasing age were found in the cavity: hornblende partially altered to chloritic material, ilmenite more or less completely altered to leucoxene, cobaltite?, apatite, massive pyrite, chalcopyrite?, siderite, graphite, ankerite, quartz, finely crystalline pyrite, galena?, sphalerite, and calcite.

Adjacent to the cavity was a fracture on whose face were slickensides, indicating at least minor displacement. The presence of calcite in this fracture suggests that it may have been the channel through which the minerals were introduced into the cavity.

DESCRIPTION OF MINERALS.

The non-opaque minerals in the deposit were identified by optical properties of powder in refractive index liquids. Refractive indices are not recorded here because the liquids used were not sufficiently numerous or carefully standardized. Qualitative chemical wet tests were used for corroboration of microscopic evidence, and as the chief means of checking the identity of the opaque minerals.

Hornblende forms prisms as much as 2 by 7 cm on which the following faces may be readily identified: prism, clinodome, clinopinacoid, and orthopinacoid. The clinodome appears to be (021), the angle (021) $\wedge$ ($0\bar{2}1$) being roughly 62°. The angle from the edge between these faces and the edge

[1] Published by permission of the National Lead Co.

[2] Stephenson, R. C., The titaniferous magnetite deposits of the Lake Sanford area, New York: New York State Mus. Bull. 340, 1945.

between (110) and (110) was measured as 104°. Some crystals show broken, slightly displaced sections that have been cemented together again. The freshest material is black in the hand specimen. Under the microscope X is pale brown, Y olive green, and Z dark smokey green. 2V appears to be less than 65° and the extinction angle Z $\wedge$ c at least 19°. Crystals grow on garnetiferous anorthosite of the cavity wall.

The chloritic material into which the hornblende is more or less completely altered is apparently composed of several minerals of moderate refractive index forming a felty mass. One is pale brown with little pleochroism and low birefringence. Another is darker brown with distinct pleochroism and moderate birefringence.

Ilmenite occurs in crystals as much as 10 cm long. They have well developed basal parting, which in places is warped in the larger crystals. Crystal faces are commonly present, best developed on the smaller crystals. The basal pinacoid and rhombohedron are recognizable. Wet assay of material from one of these crystals that had been digested in cold dilute acetic acid to remove calcite gave the following values: TiO_2 48.5%, Fe 37.6%. This indicates ilmenite 94% and magnetite 4%. The magnetite occurs as small dull plates on the basal parting of the ilmenite. They can be readily removed with a knife and picked up with a magnet. Where ilmenite-leucoxene is in contact with hornblende, neither mineral has crystal faces developed against the other, indicating an overlap in crystallization period. Since ilmenite-leucoxene is separated from the cavity walls by hornblende it must have started to crystallize after the hornblende. This vug ilmenite shows larger crystals and a lower proportion of magnetite than any other type of ore in the mine.

Cobaltite occurs as only a few small grains not sufficiently abundant to make its identification entirely free from question. One equant grain with indications of crystal faces may be a pyritohedron. It appears to be automorphic against ankerite and massive pyrite near a hornblende crystal.

Apatite was found as a single crystal 1 cm across of a pale pink color that makes it resemble orthoclase. It lies between altered hornblende and quartz.

Pyrite occurs as coarse grained masses up to 1 cm across, with poorly developed crystal faces that may be pyritohedrons. It was noted resting on hornblende and ilmenite-leucoxene crystals, with tongues penetrating them. Minute octohedrons also occur crusting the terminations of quartz crystals in open cavities, indicating two generations of pyrite.

Chalcopyrite occurs only as a few small grains identified entirely on the basis of color. They appear to be associated with pyrite and carbonate in hornblende.

Siderite is light brown in color, medium grained, and not very abundant. It forms thin crusts on massive leucoxene, and encloses hornblende crystal terminations.

Graphite was identified by its being soft enough to mark paper, black opaque, and of lower specific gravity than bromoform. It occurs in thin films on hornblende crystals at ankerite contacts, but was not noted elsewhere.

Ankerite is pale gray and of a dull luster as compared with calcite. It forms very coarse grained masses as much as 4 cm across, resting on hornblende crystals and massive pyrite.

Quartz is white for the most part. A little of it is pale but distinctly amethyst. It commonly shows small but well developed faces lining cavities. When calcite is digested with HCl an anhedral sponge of quartz is sometimes left, indicating an overlap in the crystallization period of the quartz and calcite. Quartz encloses crystal terminations of hornblende and ilmenite-leucoxene, and quartz crusts appear to overlie ankerite. Elsewhere in the mine they occur on siderite.

Galena was identified entirely on the basis of its color, luster and cubic form. A single very small grain caught between faces of quartz crystals was found.

Sphalerite, resinous brown, occurs as occasional small grains embedded in quartz, in places associated with fine grained pyrite.

Calcite is white with cleavage faces up to 3 cm across. It appears to be the final mineral deposited in the cavities, more or less completely filling the space inside quartz crusts, and partially enclosing sphalerite grains caught on the surface of quartz crystals. It fills cracks and parting planes in leucoxene and ilmenite, and encloses crystal terminations of hornblende and ilmenite-leucoxene. It overlies poorly crystallized massive pyrite, and siderite crusts, and appears to form crusts on ankerite.

The leucoxene has a clay-like, pale blue-gray color in the hand specimen. Under the microscope it is opaque by transmitted light, chalky white by reflected light. It forms an outer layer up to about a centimeter thick on the larger ilmenite crystals. The basal parting of the ilmenite can be traced through into the leucoxene, and in some cases the ilmenite can be seen to feather out into the leucoxene as residual fragments. Small crystals of ilmenite appear to be entirely changed to leucoxene. A few of these show the crystal form of the ilmenite well preserved, with the basal pinacoid and several rhombohedral faces readily identifiable on a single crystal 2 cm across. Some of these pseudomorphic crystal faces have a waxy, pitted appearance that suggests corrosion has occurred.

An assay of material that had been digested in dilute HCl to remove carbonates, and showed no appreciable amount of impurities under the microscope, gave TiO_2 64.7%, Fe 0.5%, volatile at red heat 0.7%. X-ray examination of two specimens shows them to contain between 50 and 70 percent rutile, the balance being quartz in one case and sphene in the other.[3] Thus the leucoxene in this one occurrence bears out the view that the composition of this substance is not constant.[4]

MODE OF ORIGIN.

A number of cavities more or less completely filled with a similar sequence of minerals have been encountered in the mining operations at Lake Sanford. All of them have been found within several hundred feet of a fault along which movement of the order of magnitude of a hundred feet has occurred.

[3] Personal communication from Dr. S. S. Cole of the National Lead Co. research laboratory, South Amboy, N. J.

[4] Dana's System of Mineralogy, 7th Ed., vol. 1, p. 560, 1944. Allen, Victor T., Leucoxene problem: Program of Annual Meetings of the Geological Society of America, abstract, p. 14, 1949.

It seems likely that the cavities were formed by the fault movement, and filled by solutions that moved along the fault plane and associated fractures. The slickensided, calcite-filled fracture adjacent to the pocket from which the leucoxene specimens were taken could have provided access to that particular cavity. That movement took place subsequent to the formation of the ilmenite and hornblende crystals in the cavity is shown by the bent parting planes in the former, and the broken, displaced segments of the latter. This movement may well have been part of the fault movement.

The exceptionally large size of the ilmenite and hornblende crystals suggests that they were formed under deep-seated conditions involving volatile constituents. That such conditions existed when solutions were passing through the fault fractures is attested by localization in and near the fault of biotite books with cleavage faces as much as 5 cm long, unusually large garnet masses, and extensive scapolitization. Before deposition was completed the solutions must have cooled to rather low-temperature hydrothermal conditions as indicated by the formation of chloritic material in the cavity and the deposition of calcite in the cavity and the fault fractures.

No conclusive evidence has been found to demonstate the stage at which the ilmenite was altered to leucoxene. Removal of iron in the transformation of ilmenite to leucoxene might produce a decrease in volume. This would explain the apparently greater abundance of calcite in leucoxene than in ilmenite. That some earlier mineral of the series found in the cavity did not fill the shrinkage spaces in the leucoxene suggests that the transformation had not occurred before the stage at which calcite formed. Thus the balance of evidence suggests that the leucoxene formed rather late.

ACKNOWLEDGMENTS.

In the preparation of this paper the writer is indebted to B. K. Haffner Jr. for illuminating discussions of the material collected, to H. M. Davies for work on the material beyond the call of duty in the assay laboratory of the Sanford mine, and to J. J. Rogers, Casper Mathie, and R. V. Gaines for additional material which they collected.

CORNELL UNIVERSITY,
ITHACA, NEW YORK,
Feb. 1, 1950.

SCIENTIFIC COMMUNICATIONS

THE OOLITHIC HEMATITE DEPOSITS OF EGYPT.

This is a short note on the discovery and occurrence of the oolithic hematite deposits in Egypt.

The slogan that Egypt could not be industrialized because of the absence in it of iron ore and coal was first broken by the discovery of the above mentioned deposits by the Egyptian mining engineer Labib Nassim [1] in 1917. Coal has not been discovered in Egypt, but petroleum is being produced on the shores of the Gulf of Suez and the Red Sea. Petroleum coke could be used for the reduction of the hematite and heat could be supplied by fuel oil or by electricity from the Aswan dam electrification project under execution. Limestone is also available. Manganese,[2] chromite,[1] nickel ore [3] and abundant refractories would be available for a steel industry in the country.

The hematite deposits lie east of Aswan, at latitude 24°6′, longitude 32°54′, in an area bounded on the west by the Nile valley along a stretch of 25 km and extending eastwards for a length of about 50 km. The area is traversed by three main valleys: the Wadi Abu Subeira, the Wadi Abu Agag, and the Wadi Allawi.

Between the first two valleys the area is a dissected plateau overlooking the Nile valley with an escarpment 100 m high and 200 m above sea level. Its surface rises gradually eastwards until it attains a height of 300 m above sea level near its eastern limit at Wadi Allawi.

The Nile and the Egyptian State railway constitute the main means of communication between the area and the Mediterranean Sea. The railroad is now being extended southwards to join the Anglo-Egyptian Sudan railway at Wadi Halfa and will pass up Wadi Abu Agag tapping the central part of the hematite deposits.

History.—The hematite has been worked by the ancient Egyptians who ground it for use as a red pigment for paints and inks, which can still be seen in the paintings on the walls of their temples and tombs and in their writings on papyrus. The adits of their underground workings on both banks of Wadi Abu Subeira were filled up with rubble stone and carefully camouflaged with heaped earth when abandoned, probably under pressure of foreign invasion.

[1] Nassim, Labib, Minerals of economic interest in the deserts of Egypt: Inter. Geogr. Congress, pt. 3, pp. 163–168, Cairo, 1925. Hume, W. F., Geology of Egypt. Vol. II, The fundamental Pre-Cambrian rocks of Egypt and the Sudan, their distribution, age and character. Pt. III. The minerals of economic value, Government Press, pp. 851, 853, Cairo, 1937.

[2] Ball, J., The geography and geology of West-Central Sinai, Government Press, pp. 186–204, Cairo, 1916.

[3] Nassim, G. L., The discovery of nickel in Egypt: Econ. Geol., vol. 44, pp. 143–150, 1949.

Some of these adits were opened in 1921 by the discoverer and many more are still closed as left by the ancient miners. The epoch at which these deposits were first worked for pigments is estimated to be Predynastic, some 6,000 years ago.

The date when metallic iron first came into general use in Egypt has always been a subject of controversy. The earliest objects of iron found in Egypt are beads of Predynastic date. On analysis these were found to contain nickel [4] and were, therefore, considered to be of meteoric origin. The writer would like to point out that iron beads containing nickel have been found by her in the slag heaps left by the ancients in the Ab Swayel Copper-Nickel mine, which was worked in Predynastic times.[5] The ore of this mine contains sulphides of copper, nickel, and iron, and during reduction of the copper ore, portions of the iron and nickel contents of the ore were reduced and trapped as beads in the slag. Such beads were probably used for ornamental purposes or may have been beaten together to form other small objects. Therefore, the presence of nickel in iron objects found in ancient tombs cannot be taken as a definite proof that such objects were necessarily made of meteoric iron.

Even if we eliminate all of the non-rusting iron objects found in tombs, under the assumption that they are of meteoric origin, or are residues from their metallurgy of the Ab Swayel copper, we are left with the oldest iron object found in a tomb of the 4th dynasty in the Mycerimus Valley Temple at Giza near Cairo. This was found completely rusted and formed part of a "magical set." [5] Small objects were found in later dynasties but it seems that iron only came into general use, particularly for quarrying purposes, about the 26th dynasty.[6]

No implements were found in the Aswan hematite mines except a wooden mallet and a wooden peg in one of the ancient adits, which tends to indicate that the ore was used mainly for pigment.

Since its re-discovery in 1917, the hematite has been prepared by the discoverer in his factory at Cairo as a red oxide of iron pigment for local and foreign consumption. Its use for the manufacture of iron and steel is at present contemplated.

Geology.—The hematite constitutes one stratum or more of the Nubian Sandstone Series generally considered as being of Upper Cretaceous age. This series is composed of alternate strata of sandstone, grit, clay, and hematite, overlying Precambrian granites and schists. The lowest bed is a coarse kaolinic conglomerate and the topmost bed is a hard quartzite; the hematite beds occur about the middle of the series. The following represents a section of this series in the Nile valley overlooking Aswan.

[4] Desch, C. H., Report on the metallurgical examination of specimens for the Sumerian Committee of the British Association: Rept. Brit. Assoc., pp. 437–441, Glasgow, 1928–1929.

[5] Dunham, D., and Young, W. J., An occurrence of iron in the 4th dynasty: Egyptian Archaeology Jour., vol. 28, pp. 57–58, 1942.

[6] Lucas, A., Ancient Egyptian materials and industries, p. 272, E. Arnold and Co., London, 1948.

Quartzite	10 m thick
Yellow sandstone	30 m
Oolitic hematite	5 cm
Refractory clays	8–10 m
Ferruginous sandstone	1 m
Iron ore beds (see below)	
Ferruginous sandstone with iron concretions	10 m
Clayey sand with thin sandstone beds	12 m
Coarse-grained yellowish sandstone	10 m
Kaolinic conglomerate	12 m

These beds lie horizontally on eroded Precambrian rocks.

The iron ore beds in places have little or no cover and could be mined by open cut, but along the Nile escarpment and on both banks of Wadi Abu Subeira underground methods of mining would be necessary.

The area is cut by NW-SE faults trending with displacements up to 30 m. Otherwise the ore beds are more or less horizontal with a few dips of 5 to 10 degrees. On the northern end of the area, a WNW-ESE fault drops the whole Nubian sandstone formations for an unknown distance, and with it the hematite beds. North of this fault the hematite is not exposed even in deeply cut valleys.

Erosion and an area of igneous rocks limit the hematite on the southern and eastern sides of the area and it is not found west of the Nile valley.

The Ore Deposit.—The ore consists of rounded or flattened hematite oolites ranging between 0.5 to 1.5 mm in diameter embedded in a matrix of hematite. The impurities are mainly silica in the form of rounded grains of sand, aluminum silicate in the form of clay, and smaller quantities of calcium phosphate and manganese dioxide.

The ore occurs in three horizons:

(1) The lowest oolitic bed ranges between 40 to 50 cm in thickness and is everywhere overlain by a ripple marked, brownish, ferruginous sandstone and is not continuous throughout the area, although the ripple marked bed is continuous.

(2) The central oolitic bed ranges between 50 to 150 cm in thickness and is continuous throughout the area. Its horizon is about 8 m above the lowest bed from which it is separated by fireclay.

(3) The upper oolitic bed ranges between 40 to 70 cm, is not continuous throughout the area, and is separated from the central bed by a ferruginous sandstone that rarely exceeds 1 m, and which in places disappears leaving the central and upper oolitic beds in contact with each other, but marked by a bedding plane.

Each of the oolitic beds is more or less homogeneous in composition and thickness over large areas, and the three do not differ much in their composition and analysis. They can be distinguished only by the horizon they occupy.

The following table gives an average of 15 analyses of representative samples taken from different parts of the area.

Fe	SiO_2	P	Mn	CaO	MgO	S	Al_2O_3	Loss on heating
55.4	8.88	0.92	0.29	2.92	0.78	0.06	2.73	2.38

The iron ore area under heavy overburden is about 188 sq. km, and that available to open cut is 61 sq. km. Using an average thickness of 1 m, the approximate tonnage would be 183 million tons of more or less superficial ore and 564 million tons of ore under overburden. This is exclusive of beds of non-oolitic, siliceous hematite that averages 25 to 35 percent Fe.

The genesis of the Nubian Sandstone Series is a problem of its own, but the ripple marks and false bedding of the sandstone and the prints of leaves in the clays seem to indicate that the Nubian Sandstone Series, including the oolitic hematite, have been deposited in shallow water. The sandstone series overlies Precambrian igneous rocks more or less horizontally. This feature was observed as far south as latitude 23° and as far north as latitude 30°. It is thus evident that the Precambrian rocks were eroded almost to a plane before the deposition of the sandstones. The Nubian Sandstone and included hematite beds were laid down on this surface and the iron was probably supplied by the weathering of iron-containing minerals in the Precambrian rocks.

GERTRUDE LABIB NASSIM.

ABBASSIA, CAIRO, EGYPT,
April 27, 1950.

DISCUSSIONS

"PNEUMATOLYSIS" AND THE LIQUID INCLUSION METHOD OF GEOLOGIC THERMOMETRY.

(A REPLY TO G. C. KENNEDY).

INTRODUCTION.

Professor Kennedy very kindly gave us the opportunity to read and prepare comments on the above paper before publication. We wish to congratulate him on the general excellence of his criticism. It is a service to the science to examine critically new developments and conclusions, but since we feel that some of his viewing-with-alarm is the result of erroneous reasoning, we welcome this opportunity for immediate reply.

The points raised by Professor Kennedy are directed in large part against the temperature-pressure research being conducted in this laboratory. Accordingly, the following reply is a cooperative effort by the staff and students who have had most to do with the development and use of the decrepitation technique. We have considered each argument individually and in the order with which they appear in this paper.

DISCUSSION.

"Certain assumptions are implied by Smith . . . : 1. Deposits formed at 390° C and under a pressure equivalent to two miles of rock could not have been formed from a gas." It should be noted in the original paper, this was not an assumption, but derived from the data (1) the minerals decrepitated, (2) the minerals contained liquid inclusions with a degree of filling sufficiently great that decrepitation could be the result of the explosion of the liquid inclusions. Whether or not we should term a high density aqueous fluid a liquid or gas will be discussed below.

2. "'True' pneumatolytic deposits could be detected by a decrepitation curve." As we have frequently pointed out, and as Kennedy himself clearly shows, there should be no sharp point of beginning of decrepitation due to liquid inclusion explosions if the degree of filling of the inclusions is small. The terminology of gas and liquid arises again and will be discussed below.

3. "A reasonable correction to the temperature of disappearance, resulting from the pressure under which the deposits were formed, has been made." It should be kept in mind that the main question before us is the density of the depositing fluids, and not the temperature or pressure. We measured approximately the degree of filling of the fluid inclusions in the Cornish minerals and found that it was fairly large. If the liquid in these inclusions were pure water, the density of the fluid trapped in the inclusions with the smallest degree of filling would be approximately 0.7. Water in the form of gas at 345° C and

under the highest pressure possible (the vapor pressure), would have a density of approximately 0.1. Again we come to the question of terminology.

4. "The coefficient of expansion of vein-forming or ore-carrying solutions is the same as water." This is a valid criticism, but since little data are available on (1) the composition of the liquid inclusions, and (2) the p-v-t relations for all possible hydrothermal solutions, the best we can do is assume that the solutions are dilute and aqueous and that even though the vapor pressure curve is not the same as that of water, the slopes of the iso-volume lines in the p-t plot are the same as those of water. Certainly this is a first order approximation, and as long as the primary data of the degree of filling of liquid inclusions are recorded, the results of calculations can be modified later when the necessary p-v-t relations are established.

5. "The temperature of filling of a vacuole has a unique significance, that is, there has been no transport of material to or from the vacuole since its formation." We agree that this is our basic assumption and if it can be demonstrated that fluids may enter and leave the inclusions according to the ambient pressure, then the degree of filling is not a direct function of the temperature-pressure relations when it was first formed. We have good data, outlined later, that show that if any changes do take place they are very slow, even over times of the order of magnitude of the age of the oldest known rocks, and there are fair data that there have been no measurable changes. This will be discussed below.

". . . at 390° C water would be gaseous, not liquid, as 390° C is above the critical temperature of water." This statement is criticized in the discussion that follows.

"Smith implies . . . that he chooses to call all gases under supercritical pressures 'liquids'." Unfortunately, this misinterprets the statements actually made. The point that was being made, is that since the states of gas and liquid are *continuous* with changes of temperature and pressure (except in the small area of change below the critical pressure and critical temperature simultaneously) then the terminology cannot be *discontinuous*. We can define an ideal liquid, as a fluid state of matter in which the constituent atoms, ions or molecules are in constant electronic interaction which provides a force of cohesion lacking in the ideal gas. Conversely, an ideal gas is a fluid state of matter in which the constituent atoms, ions or molecules do not electronically interact. The continuous transition from liquid to gas can then be treated as a decrease in the amount of interaction between the components, this being a direct result of a decrease in density. Therefore, under supercritical pressure conditions, if a fluid has a high density and other properties like normal liquids, we would prefer to call it a liquid, but if it has a low density and other properties like normal gases, we would prefer to call it a gas.

"Such terminology, however, is most unfortunate and can only lead to confusion." It is granted that some geologists might be confused by this approach, so that some compromise is desirable. It is suggested that the critical density of the solutions be taken as the limit of what should be termed hydrothermal (liquid) solutions and pneumatolytic (gaseous) mixtures. This separates effectively the fluids in inclusions of vein minerals (minimum observed density

about 0.6) from the fluids that have been seen to deposit encrustations in fumarolic vents (density unknown, but very much less than the critical density of water — 0.4). If the terms are used in this way, then fluid inclusions can be used to differentiate the two kinds of transport. If the liquid phase fills the inclusions before the vapor phase during heating, the transporting agent was a hydrothermal solution. Conversely, if the vapor phase fills the inclusions before the liquid phase during heating, the transporting agent was a pneumatolytic mixture.

Professor Kennedy uses the terms in part in the above manner, since later he states: "In . . . (the case of a vacuole in which the amount of liquid per unit volume in the vacuole is less than that for liquid at its critical density) . . . there is a decrease in the rate of pressure rise once the fluid in the vacuole becomes homogeneous. This would be the case for any pnuematolytic deposit formed at supercritical temperatures and subcritical pressures."

"Uniformity of liquid content in the vacuoles seems to indicate not necessarily little or no leakage as postulated by Ingerson, but a long period at one temperature and pressure during the history of the mineral, in which equilibrium was established." The implied uniformity of degree of filling of liquid inclusions is not a fact. For example, in the quartz veins of the Canadian Shield, especially in the gold camps, uniformity of degree of filling is rare. The usual condition, seen under the microscope and recorded in decrepigraphs, is a set of what appear to be primary inclusions with a large bubble which decrepitate at 310° ± 50° C, and a set of what appear to be secondary inclusions with a very small bubble which decrepitate at 140° ± 60° C. Any theory of adjustment of degree of filling to ambient pressure must account for this relation. The gold mining areas in which the multiple sets have been found include the Porcupine, Kirkland Lake, Larder Lake, Rouyn, Cadillac, Malartic, Bourlamaque, Michipicoten, Little Long Lac, Pickle Crow, Lake of the Woods, Sioux Lookout, Savant Lake, Red Lake, Uchi Lake, Central Manitoba, Favorable Lake, Herb Lake, Flin Flon, Yellowknife, and Indin Lake areas. In addition, a number of quartz veins occurring in nonproductive areas have been tested with similar results. Even the pegmatite veins in the Southeastern Manitoba region, which contain uranium minerals calculated to be of the order of 2 billion years old on the basis of U/Pb and Rb/Sr methods, give similar results. The two sets of liquid inclusions have retained their identity with regard to different degrees of filling in this very ancient area of the world, which suggests that if there is leakage and/or filling of inclusions after entrapment, it is a remarkably slow process.

Of the two kinds of fluid inclusions in the Canadian Shield vein minerals, one would expect the secondary type, being in cracks which traverse crystal boundaries, to be the more easily affected by the ambient pressure. If adjustment were possible, one would expect the degree of filling of the secondary inclusions to be related to the present surface, which represents an ancient peneplain, but we have found large horizontal variations which can be systemized and contoured in a regional way. Also, if adjustment were possible, one would expect that within one mine, the degree of filling would be a simple function of depth, but we have found a complex pattern of degree of filling, which can be

rationalized with regard to the position of ore shoots. Fluid inclusion filling temperature gradients up to 10° C per 100 feet horizontally, with maxima and minima differing by 40° C horizontally have been measured in vein quartz in several gold mines. These data are being prepared for publication.

"The difficulties in the interpretation of decrepigraphs are at once apparent by examination of the graphs published by Smith and his students." It is true that decrepigraphs prepared by the mental integration method, used earlier by one of us (H.S.S.) are open to some subjective errors. However, the newer method which we now use exclusively involves an integration by an electronic calculator designed to record the rate of explosions loud enough to activate the electronic relays. It should be noted that the amplitude of the sounds beyond the threshold value does not modify the shape of the decrepigraphs. We do not claim that the interpretation of decrepigraphs is simple. However, we have several kinds of independent controls which have been used to check the interpretation, including (1) decrepitation of synthetic quartz grown by Dr. Hale of the Brush Development Company, (2) decrepitation of synthetic halite and calcite grown in this laboratory (by F. G. Smith and P. A. Peach), (3) decrepitation of Tri-State sphalerite which has been studied by Professor Newhouse by the heating stage method, (4) decrepitation of pegmatite quartz which has been studied by Dr. Ingerson by the heating stage method, (5) decrepitation of quartz and fluorite in which two types of inclusions with different degrees of filling were observed under the microscope, and (6) decrepitation of apatite containing linear liquid inclusions the degree of filling of which could be measured under the microscope.

We use petrographic methods as control in interpreting decrepigraphs. For example, liquid inclusions in some of the Cornish minerals were observed to have a degree of filling greater than the critical degree of filling, and similar to that in primary inclusions in quartz from Canadian Shield veins. Consequently, decrepigraphs of certain Cornish and Canadian minerals would be expected to have a similarity. The recorded decrepigraphs are similar in the 300–400° C range.

It should be mentioned here that the correction for pressure would be greater for the Shield deposits than for the Cornish deposits, so that if the latter are termed "pneumatolytic" on the basis of temperature rather than on density of the transporting fluids, then the Canadian Shield quartz veins would also have to be classified in a similar way. On the basis of pyrite geothermometer measurements, we have determined that the temperature of deposition of the early pyrite and quartz of these veins was between 450 and 650° C. The pressure correction we have calculated to be of the order of 6 to 8 miles of rock load.

We are aware that decrepitation may be caused by changes in crystals during heating other than the filling of liquid inclusions. The cause and interpretation of such anomalous sounds during heating are being investigated in this laboratory.

"For pyrite, . . . (Scott) selects the point 115° C . . . he might equally as well have selected the point at approximately 225° C. . . ." It should be emphasized that the decrepigraphs obtained during early stages of the work were plotted by estimating the frequency, while actually listening to the decrepi-

tation. Minor, closely spaced variations in frequency tend to be diagrammatic for this reason. It was hoped that the effect of the personal element and human limitations in such estimating would be indicated by the descriptive, if unorthodox, divisions of the ordinate of each graph. Concerning the quoted objection, Professor Kennedy argues that several filling points may be interpreted from the graph for Ivigtut pyrite. There is admittedly room for difference of opinion in this case, and the method of recording should carry only part of the blame. However, if a smooth, "average" curve be drawn from the pyrite decrepigraph, it will be found that the frequency rises rather uniformly from 115° C, and the slope of the curve is already very steep by about 200° C. Thus, its increase at about 220° C is no longer pronounced, and the lower temperature, 115° C, must be chosen.

Professor Kennedy draws comparison with the curve for siderite from Ivigtut. Here an "average" curve must rise sharply at 160° C; below that temperature the slope is only moderate. Therefore, the point of sudden rise—160° C—was chosen as the lowest filling temperature of the primary fluid inclusions. An additional fact, not mentioned in the paper concerned, aided in the interpretation of this curve. The siderite contains more fluid inclusions than the pyrite, and many of these are secondary, lying along cleavage planes and fractures. Thus preliminary decrepitation is to be expected.

"The graph for the Pointe du Bois beryl . . . is obviously meaningless, as the temperature of 390° C is above the critical temperature of water. . . ." The original paper may be quoted in reply: "This is above the critical temperature, so that even after moderate allowance for overshoot the fluid in the inclusions must approach critical density. It is therefore surprising that so definite a decrepitation point was recorded." Despite objections and difficulties in explaining this observation, a distinct frequency rise *did* occur, and some reason for it must be sought. Professor Kennedy evidently discounts the explanation given with the graph. Possible alternatives are outlined below:

(a) The critical temperature of the included fluid may be above that of pure water.

(b) The overshoot for beryl may be greater than might be expected from that of quartz.

(c) The original graph shows that the decrepitation was not loud—indeed, it was barely audible at 390° C. This condition suggests that the stethoscope technique may have failed to detect the initial portion of the decrepitation curve, so that the frequency of popping when first heard was already high.

"At the end (of an experiment in which a plate of fluorite was subjected to a temperature of 150° C and water pressure of 1500 bars for two weeks) *it was noted that the temperature of disappearance of the vapor phase in those vacuoles reexamined had been lowered approximately 10° C."* We contend that the data from this experiment do not prove that the degree of filling of all of the inclusions in the fluorite was modified by the temperature-pressure treatment. Apparently some were modified, but it is not reported whether all were modified. The temperature of filling of the inclusions examined (number not stated) is said to be of the order of 200° C. If the inclusions reached equilibrium with the liquid during temperature-pressure treatment, the temperature of filling in the laboratory should be well under 100° C, not

190° C as stated. It would seem from the experimental data that the *average* temperature of filling of inclusions reexamined was lowered 10° C.

Averages are nearly meaningless in the study of data where there is a scatter due to one or more causes combined with subjective error. It is necessary to plot frequency of occurrence of values against the values and if the resultant curve is of the error function type, to choose the median value. If it can be shown that the temperature of filling determined in this way can be chosen well within ± 10° C, and if the temperature can be shown to shift 10° C after pressure treatment, then we must accept the conclusions reached by Professor Kennedy. Merely because a few inclusions were in communication with the outside of the crystal tablet and received more liquid during pressure treatment, thus disturbing the average result, is no proof that all of the inclusions were affected. (Herein lies an advantage of the decrepitation method: the effects due to many thousands of inclusions are analyzed simultaneously and departures from the norm have only a small effect on the final results.)

Another objection that may be made to the above experiment is that some mineral other than fluorite should be used for such important tests. We have noted that fluorite commonly contains inclusions along cracks (which may be lineage boundaries, or may be gross cracks due to later deformation) that might allow entry of liquid from outside the crystal. In addition, the easy and multiple cleavage of the mineral and possibility of minor cracks being formed during grinding in preparation of the tablet is more than possible; it is probable. We suggest that quartz would be much better for tests of the above type. In addition to being strong and tough, it has a wide range of temperature of deposition and occurs in many different types of mineral deposits.

CONCLUSIONS.

Professor Kennedy's criticism of the fluid inclusion method of geologic thermometry in general, and of the decrepitation method in particular, is apparently sound with regard to some but not all of the assumptions and methods of calculation. The experimental evidence for his hypothesis that the degree of filling of inclusions is modified in a gross way after formation is not conclusive.

It is suggested that, in order to avoid quibbling over the terminology of natural gases and liquids near the critical conditions, the term *hydrothermal solution* be used for natural aqueous solutions with a density greater than the critical density, and the term *pneumatolytic mixture* be used for natural gaseous mixtures with a density less than the critical density.

The decrepitation method of measuring the degree of filling of fluid inclusions in minerals is on a reasonably sound basis of fact, but is open to quantitative improvements in the correction for pressure.

F. G. SMITH, P. A. PEACH, H. S. SCOTT, A. D. MUTCH,
G. D. SPRINGER, R. W. BOYLE, AND W. M. M. OGDEN.

GEOCHEMICAL LABORATORY,
DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, CANADA,
April 11, 1950.

REVIEWS

The Geology, Paragenesis, and Reserves of the Ores of Lead and Zinc. Edited by K. C. DUNHAM. Pp. 400; figs. 99. Part VII, Symposium and Proceedings of Section F, of the Report of the XVIII Intern. Geol. Congress, Great Britain, 1948. London, 1950.

This book is an authoritative review of resources in lead and zinc deposits, sponsored by the International Geological Congress and it embodies papers and discussion submitted at the London session. It has become customary to hold such a symposium each time the congress convened since 1910. The volumes on iron ore, coal, petroleum, and copper resources are standard references of inestimable value and to them is added this new one on lead and zinc. The topic was conceived by W. R. Jones and brought to fulfillment by the unflagging effort of the Secretary, K. C. Dunham. Papers ranging from good, through indifferent, to definitely poor, include 11 from North America, an outstanding one from South America, 2 from Australia, 4 from Africa, 15 from Europe and 1 from Asia. Contributed discussion on Broken Hill (N. S. W.) and the Kupferschiefer promise additional knowledge on these important areas. An excellent bibliography accompanies both the Secretary's summary and most of the articles. Dunham elicited statistics from mining houses and government agencies, only that biggest corporation of all, the U. S. S. R., abstaining (p. 12) from participation; the data form a basis for a new statement on the lead and zinc supply that was comforting to the persons in attendance. The introduction is actually a concise summation of all pertinent data and it brought out the new concept that one-quarter of production now and over one-third of the known reserves are in hypothermal deposits, with mesothermal and telethermal ores essentially tied for second and third places.

Production of lead rose on a "population increase curve" up to 1924 and has remained steady since at slightly over 1,500,000 tons annually showing only cyclic short turn fluctuations. On the other hand zinc has continued to rise to 1,875,000 tons per year.

Several included papers and some discussion deserve special commendation for required reading. A few are singled out, either for single merit or for extension of data therein. Discussion of the Broken Hill (N. S. W.) paper brought forth preliminary announcement of a monograph describing the geology and gives much new and pertinent data on hypothermal deposits, which type seems to be the hope for the future. Trepça is listed under pyrometasomatic-mesothermal deposits and is a masterly presentation of the quantitative distribution of metals and of the relation of ore to structure. However the article indicates quite clearly that the ores did not originate in any igneous body in contact with them, and the classification may be questioned. The deep mesothermal veins and replacements, like the hypothermal types, need a more complete description. Leptothermal veins and replacements, in all their variety, are described in the article on "Lead and zinc deposits of the Cerro de Pasco Copper Corporation in Central Peru"; the interrelations of regional structure, intrusive bodies, ore host and structure for this ore type are described clearly and concisely. Telethermal replacements and disseminations are represented by excellent papers on "Lead and Zinc in Poland," the Mechernich-

Maubach area in west Germany, and the Kupferschiefer. Many readers would be sympathetic to the opinion of Brown, Westoll and others that lithification of the Kupferschiefer was in places well advanced before the sulfides were emplaced and that any simple syngenetic origin is open to question.

An extensive bibliography accompanies each contribution. Dunham's summarized geology of the principal lead and zinc mines of the world includes at least one reference to each listed occurrence although the reviewer would comment that the reference is often more sketchy than Dunham's summary and credit has been given where very little was due.

The reviewer would add a few comments first on distribution of reserves in the world structural pattern, second on amount or size of deposit, and third on deposit type and pertinence of structure to exploration, in order to show that the information in this useful book is far from exhausted and that the data therein are worth extensive study.

In the first category, Dunham calls attention to the paramount position of hypothermal deposits in carrying one-third of the reserves of lead and zinc. Apparently he conceives of shields as the favored home of hypothermal deposits and states:

"the contribution to world production made by deposits in the pre-Cambrian 'shield' areas of Canada, Fennoscandia, Australia and Africa has only become significant during the present century, but it seems likely that all these areas offer further opportunities for the discovery of major reserves—perhaps the best opportunities which now remain."

Few geologists would agree that 2,000 square miles of the Broken Hill (N. S. W.) old-mass is great enough area to be a shield. Certainly both Broken Hill and Mt. Isa lie east of the area accepted usually as the Australian Shield. Only Tsumeb, Broken Hill and the Congo Border deposits with 1,405,000 tons of lead and 3,875,000 tons of zinc lie within the confines of the Rhodesian Shield. The Fennoscandian Shield lists only 590,000 tons of lead and 2,475,000 tons of zinc. The Canadian Shield statistics show only 28,000 tons of lead and 3,827,000 tons of zinc although these figures should be revised upwards at least slightly. This accredits less than 7 percent of lead reserves and under 20 percent of the zinc reserves to Shield areas; production credit is likewise low. Actually over half of the lead reserves and over one-third of the zinc reserves are in elongate mountain masses which have been peneplained at least once since the deposits were formed. Such large size earth structures, of elongate rather than shield form, have been the outstanding contributors of the nonferrous base metals and apparently lead and zinc are no exception.

The second category of comment serves to emphasize a conspicuous feature of the statistics. The accredited reserves are in a few areas; for lead, 12 areas of over 500,000 tons reserves each account for 60 percent of world resources and 17 areas of over 1,000,000 tons each account for an equivalent proportion of the zinc. As every mineral district has its big master that serves to sustain output over the hard periods, incite enthusiasm for exploration, and accounts for nearly half the output in a district, so statistics seem to show that the industry itself is sustained by the few big producers.

The third category of remarks are intended to emphasize certain extensions of study if the statistics are accepted. The rise of hypothermal and telethermal deposits to the ranking positions in reserves, raises understanding of crystal flowage to a high place in study of the former and detailed analysis of structural jointing to a prominent place in the latter. Gustafson mentions the plastic deformation at Broken Hill (N. S. W.) and calls attention to pitch reversals. Reversal of pitch

is a characteristic of flowage folds, is typical of all hypothermal sulfide bodies in the northern Appalachians and is suggested by the structural patterns of Flin Flon and Sherritt Gordon. Yet flowage folds continue to be slighted in structural geology. The telethermal deposits of upper Silesia, Mechernich-Maubach, the Tri-State District (U. S. A.) and the Touissit-Bou Becker (Mor.) area have their distribution influenced strongly by a definite stratum and also by a systematic fracture pattern related to a major tectonic disturbance contemporary with mineralization. The competency of the strata renders the fracture pattern so conspicuous that its guiding role is obvious; however the role of openings, including fractures, is not so obvious where strata are less competent, as in the Kupferschiefer; in such deposits, stratigraphic control often may seem to be the only one and appear to lend favor to a syngenetic origin of ore and sediment. This is an old thesis which plagued the Rhodesia-Congo border copper deposits—particularly Roan Antelope and N'Changa, and the carnotite occurrences on the Colorado Plateau; somewhere deposition of nearly every metal has been attributed to deposition as one component of a sediment in some fashion which no longer exists for comparative study. This reviewer has studied most of these controversial deposits in the field and in the laboratory; certainly the Richelsdorf Kupferschiefer was at least partly cemented and the organic structures were extensively calcified before the metallic sulfides came into their present position in the rock.

Accounts of some deposits, which had been discovered and developed since the XVII International Geological Congress, are so short as to give little data on metallization; the Mpanda area, and the Touissit-Bou Becker area are sketchily covered and the Russian exploration in Kazakstan and Turkistan is omitted entirely. Also certain loudly acclaimed properties, like the west end of the Sudbury Basin, have lapsed into seeming oblivion without any adequate mention or record. A geological monograph such as this, prepared for such inveterate optimists, as geologists must be, can afford to have a section to raise hope for the future and a place to air errors of past, in order that increased precision in selection of places for investigation may be achieved. This deficiency may be due in some extent to confidential data in the files of many industrial firms but the twelve papers which producing companies have assembled and released are a significant contribution to the thirty-six comprising the work. The largest mineral producer to abstain from reporting was the U. S. S. R.

The report is an essential reference work for any library where students are wont to look up data on lead and zinc supplies. It is the most accurate statement available and the most complete account of occurrences existing under one cover. Only the excellence of the work has made possible constructive comment and extensions of the articles and conclusions.

GEORGE W. BAIN.

DEPARTMENT OF GEOLOGY,
AMHERST COLLEGE,
AMHERST, MASS.,
June 23, 1950.

X-ray Crystallography, 4th Edit. By R. W. JAMES. Pp. vii + 88; 10 x 17 cm. Methuen, London, and John Wiley & Sons, New York, 1950. Price, $1.25.

According to the author's preface this book gives a brief outline of the principles underlying the methods of X-ray crystal analysis. It is designed to be interesting, as a general account, to students of other branches of physics, and at the same time capable of serving as an introduction to the subject of crystallography for those about to take up this study seriously. Brevity is achieved by the omission of de-

tailed examples which presumably must be supplied for the serious student in lecture room and laboratory. The casual reader with sufficient background of physical science will find the book well written, enlightening, and concentrated. To the reader with less preparation, the lack of more than the simplest of examples will make some parts very difficult.

HORACE WINCHELL.

Have

Psychical Physics—A Scientific Analysis of Dowsing, Radiestesia, and Kindred Divining Phenomena. By S. W. TROMP. Pp. 534; figs. 150. Elsevier Publishing Co., New York, 1950. Price, $8.00.

Those who have been wont to scoff at divining and the witch stick perhaps had better read this book. They may scoff no longer. Most mining engineers, geologists, and water supply people have held up their noses at finding water by means of dowsing. Even in A.D. 1556 Georgius Agricola in his "De Re Metallica" devoted a chapter to this subject and dismissed it as improbable. At least the scoffer should know something of the skeptical scientific approach of the geologist author of this book and review the experiments recorded therein with the same scientific unbiased approach as the author.

This book presents an analysis of the influence of electromagnetic fields on psychic phenomena in human beings and records recent experiments with artificial magnetic fields and string-galvanometers, which indicate that divining phenomena really exist and that they can be explained by normal physical and physiological laws. The conclusion is that a careful analysis of these phenomena might prove of great value to medicine. The author is Professor of Geology at Fouad I University, Cairo, Egypt, and his approach to the subject is entirely analytical and scientific. The literature covered by the author is rather amazing; the Bibliography consists of 62 pages of fine type and includes 1,496 references that cover physical, psychical, geological, geophysical, biological, medical, electrical, electromagnetic, and related fields. There is coverage of the electromagnetic fields in the body, heart, and brain, and sensitivity of animal and man to light, heat, accoustical and other types of waves.

In the first chapter there is an analysis of the electromagnetic field in and around organisms. In the second chapter evidence is presented to support the assumption that the existence of divining phenomena can be suspected on theoretical grounds. A summary is given of the different influences of electrostatic, electromagnetic and magnetic fields on living organisms. In the third chapter the divining phenomena have been analyzed scientifically and the author's experiments upon blind-folded dowsers are described. Many of the experiments took place in Holland. An appendix gives a summary of basic physical conceptions and units used. A second appendix gives notes on the sensitivity for direction of animals.

The coverage of the various subjects is quite amazing. The first chapter is really a condensed textbook on physics, radioactivity, climatology, cell development both organic and inorganic, geophysics, electromagnetic fields and experiments with them on cell growth and diseases of animals, man, and microorganisms. Much experimental work in medicine by top notch modern scientists is analyzed and discussed. Of particular interest also are parts dealing with smell and hearing of animals beyond human ranges. Many photos show radioactivity sensitivity on photographic plates of various kinds of woods. The electromagnetic properties of rocks and minerals are taken into consideration also. Many electrocardiograms of diviners are given showing their reactions in earth zones that affect dowsers.

The evidence present is very impressive and it leaves the reviewer with con-

siderable skepticism as to the correctness of his own views from now on. Certainly there are fields of sensitivity in animals and man that have not been known or suspected heretofore.

ALAN M. BATEMAN.

Advanced Atlas of Modern Geography. By JOHN BARTHOLOMEW. Pp. 155. Meiklejohn and Son Ltd., London, and McGraw-Hill Book Co., Inc., New York, 1950. Price, $6.00.

This fine new atlas, handsomely printed in Great Britain at the Geographical Institute, Edinburgh, portrays the skill of a group of modern geographers. Its 108 pages of maps in well chosen colors depict the usual geographic features and elevations by layer coloring. The preliminary pages give geographical coordinates, and how to use them; geographical terms; climatic tables; countries, states and population; world exploration; map projections; world airways; astronomical geography; geology and structure; physiography; temperature and air movements; rainfall and oceanography; climatic regions; soil, vegetation, crops; ethnology; religions; routes of commerce; and polar regions.

Then follow maps of the continents, and of the countries within, depicting geography, geology, ethnology, climate, population, and vegetation. A very detailed reference permits the finding by coordinates of some 24,000 places.

The book is a fine piece of cartography and excellent workmanship and will prove invaluable to those interested in looking up atlas features, particularly for those interested in geography, history, geology, meteorology, and agriculture.

The Statistical Year Book, 1949, of the International Tin Study Group. Pp. 232; numerous maps, charts, and tables. International Tin Study Group, 7 Carel van Bylandtlaan, The Hague, 1950. Price, $4.20.

This nicely printed volume is the first Year Book since 1939 and the most comprehensive yet printed on tin. It summarizes the activities of the old International Tin Committee and the controls exercised up to 1949. It summarizes the tin production, consumption, and uses of about 100 countries over the period 1937–48. For each country there is given the geographical position, mining methods, labor, treatment, smelting, imports, exports, consumption uses, regulations, taxation, and political factors. Tables show world tin production since 1800, prices from 1871, tinplate prices from 1851 and stocks from 1907. United States stockpiling is also considered. An English-French glossary is attached. The International Tin Study Group are to be congratulated on a fine job.

Hydrology—The Fundamental Basis of Hydraulic Engineering, 2nd Edit. By DANIEL W. MEAD; REVISED AND ENLARGED BY MEAD & HUNT, INC., UNDER THE DIRECTION OF HENRY J. HUNT. Pp. 728; figs. 397; tbls. 80. McGraw-Hill Book Company, Inc., New York, 1950. Price, $7.50.

The first edition of this book appeared three years ago and the second comprehensive edition has been thoroughly revised to incorporate the newer hydrologic data and the new ideas of Mr. Hunt developed in his extensive practice as a consulting engineer.

This edition contains a new chapter on drought, the Bergeron analysis of meteorological phenomena in terms of air mass, evaporation and measurements, artificial rainfall, the Thiessen method of weighting precipitation, rainfall and flood frequency, and many new charts and graphs.

The chapter headings are: Introduction; Water—Its Occurrence, Utilization and Control; Some Fundamental Theories; Winds and Storms; Hydrography; Atmospheric Moisture and Evaporation; Precipitation; Rainfall Measurements and Records; Annual Rainfall in the United States and Its Variation; Seasonal Rainfall in the United States and Its Variation; Great Rainfalls; Droughts; Rainfall and Altitude; Geological Agencies and Their Work; Geology; Ground Waters; Stream Flow or Runoff; Variations in Runoff or Stream Discharge; Estimating Runoff; Floods and Flood Flows; The Application of Hydrology. Literature references follow each chapter.

This volume is well illustrated, nicely printed, and will be valued by hydrologists and geologists.

BOOKS RECEIVED.

CHARLES H. SMITH AND M. L. MIGNONE.

U. S. Geological Survey—Washington, D. C., 1950.

Prof. Paper 221-B. Larger Foraminifera from the Palau Islands. W. STORRS COLE. Pp. 11; pls. 2; fig. 1. *Miocene deposits reported for first time.*

Prof. Paper 221-C. Growth Series of Ostracodes from the Permian of Texas. I. G. SOHN. Pp. 7; pls. 2; figs. 2. *Measurements of 252 specimens recorded.*

Prof. Paper 221-D. Cretaceous Plants from Southwestern Colorado. ROLAND W. BROWN. Pp. 22; pls. 4. *One group indicates Lower Cretaceous age and other Upper Cretaceous.*

Prof. Paper 224. Geology and Mineral Deposits of the Cartersville District, Georgia. THOMAS L. KESLER. Pp. 97; pls. 19; figs. 14; tbls. 4. *District underlain by Cambrian metasedimentary rocks strongly folded and by feldspathic gneisses; residual deposits of barite, manganese oxides (both mostly exhausted), brown iron, ocher, and umber, and primary bedded deposits of specular hematite.*

Prof. Paper 225. Physical Characteristics of Commercial Sheet Muscovite in the Southeastern United States. RICHARD H. JAHNS AND FORREST W. LANCASTER. Pp. 110; pls. 9; figs. 16; tbls. 14. *Period 1912–44 gave 25,028,404 pounds or 54% of U. S. production of sheet and punch mica; electrical testing and visual-electrical system of mica classification should result in considerable conservation.*

Bull. 962-C. Magnesite Deposits of Central Ceará, Brazil. ALFRED J. BODENLOS. Pp. 33; pls. 6; figs. 3. *Of the eight deposits in Precambrian crystalline limestone four were mapped and give reserves per meter depth of 251,000 tons measured ore, 421,000 tons indicated ore, and 1,291,000 tons inferred ore. Another 2,000,000 tons per meter depth may be inferred as reserve of other deposits.*

Bull. 964-C. Mica Deposits in Minas Gerais, Brazil. W. T. PECORA, M. R. KLEPPER, D. M. LARRABEE, A. L. M. BARBOSA, AND RESK FRAYHA. Pp. 101; pls. 4; figs. 33; tbls. 8. *Mica-bearing pegmatites long and thick; tabular, lenticular, irregular, and ramiform; occur in Precambrian igneous and metamorphic rocks. In September 1945 seven largest mines had total measured reserve of about 2,000 m t of mine-crude mica and total indicated reserve of about 5,000 m t.*

Bull. 967. The District of Columbia, Its Rocks and Their Geologic History. MARTHA S. CARR. Pp. 59; pls. 7; figs. 23. *Oldest rocks are Precambrian; stone is leading mineral resource. Minor iron ore, diatomaceous earth, manganese, mica, feldspar, and gold.*

Bull. 976-A. Geophysical Abstracts 140, January–March 1950. MARY C. RABBITT, V. L. SKITSKY, AND S. T. VESSELOWSKY. Pp. 69. *Nos. 11679 to 11907.*

Water-Supply Paper 1070. Public Water Supplies in Southern Texas. W. L. BROADHURST, R. W. SUNDSTROM, AND J. H. ROWLEY. Pp. 113; pl. 1. *Summarized description of supplies in 42 counties.*

Mineral Trade Notes. FLORENCE E. HARRIS AND MARY E. TROUGHT. Pp. 55; numerous tables. U. S. Bureau of Mines, Vol. 30, No. 6, Washington, D. C., June 1950. *Metals, industrial minerals and miscellaneous information.*

Illinois Geological Survey—Urbana, 1950.

Circ. 161. Secondary Recovery in Illinois. FREDERICK SQUIRES, PAUL G. LUCKHARDT, AND ALFRED H. BELL. Pp. 17; figs. 6; tbls. 3. *Statistics of results by repressuring and water flooding in Illinois to January 1, 1947.*

Circ. 163. Flooding Prospects of Illinois Basin Oil Sands. FREDERICK SQUIRES AND PAUL G. LUCKHARDT. Pp. 6; figs. 10; tbls. 2.

University of Texas Publications—Austin, 1950.

No. 4329. The Carboniferous Rocks of the Llano Region of Central Texas. F. B. PLUMMER. Pp. 170; figs. 14; pls. 23; charts 4. Price, $2.00. *Carboniferous rocks generally exposed in outer part of area, resting on older Paleozoic rocks and overlain by Cretaceous strata. Study of Pre-Carboniferous, Carboniferous, and Post Carboniferous strata. Numerous references.*

No. 5015. Index to Well Samples. DAN E. FERAY AND JASPER L. STARNES. Pp. 148. Price, $1.65. *30,000 wells from Texas arranged alphabetically by counties, companies, fee owner and number, up to June 1, 1948.*

American Petroleum Institute, Project 49, Clay Mineral Standards—Columbia University, New York, April 1950.

Prel. Rept. 5. Occurrence and Microscopic Examination of Reference Clay Mineral Specimens. PAUL F. KERR, M. S. MAIN, AND P. K. HAMILTON. Pp. 58; pls. 3; tbls. 3; figs. 10. *Results of microscopic study, correlates data with parallel studies, and interprets observations.*

Prel. Rept. 6. Electron Micrographs of Reference Clay Minerals. D. W. DAVIS, T. G. ROCHOW, F. G. ROWE, M. L. FULLER, PAUL F. KERR, AND PEGGY-KAY HAMILTON. Pp. 17; pls. 42. *Micrographs of kaolin, montmorillonite and illite groups, and certain miscellaneous or related minerals. Technique employed is described; amazing pictures.*

Canada Geological Survey—Ottawa, 1950.

Bull. 15. Actinocamax from the Upper Cretaceous of Manitoba. J. A. JELETZKY. **Sciophyllum, A new Rugose Coral from the Canadian Arctic.** P. HARKER AND D. J. MCLAREN. Pp. 43; figs. 3; pls. 4.

Mem. 255. Callum Creek, Langford Creek, and Gap Map-Areas, Alberta. R. J. W. DOUGLAS. Pp. 124; pls. 5; figs. 26; 3 maps in color. *Stratigraphy, structural geology, mechanics and regional relations; petroleum and natural gas, and coal. Appendix with description of wells.*

Ontario Department of Mines—Toronto, 1950.

P. R. 1950–4. Preliminary Report on Copper, Nickel, Lead, and Zinc Deposits of Ontario. JAS. E. THOMSON. Pp. 19; tbls. 15. *Location, ownership, development, geology, production, ore reserves (or dimensions and grade of bodies), selected references, and remarks on each mine in Ontario.*

58th Annual Report, Vol. LVIII, Part III, 1949. Natural Gas, and Petroleum in 1948. R. B. HARKNESS. Pp. 101; figs. 3; graphs 4; tbls. 18. *Mostly statistical.*

Quebec Department of Mines—Quebec, 1950.

Geol. Rept. 40. Taibi Lake Area, Abitibi-East County. RENÉ BÉLAND. Pp. 19; pls. 8; 1 colored map 26″ x 14″. *No mining properties developed or under exploration; local anomalies of strongly magnetic body—iron formation, pyrrhotite, or magnetite-rich rock—probably buried under clay.*

Geol. Rept. 41. Razilly Map-Area, Abitibi-East County. O. D. MAURICE. Pp. 16; pls. 3; 1 colored map. *Consolidated rocks all Precambrian, predominantly part of great granitic mass. Possibility of ore concentrations of economic interest.*

Geology of Central Ayrshire, 2nd Edit. V. A. EYLES, J. B. SIMPSON, A. G. MACGREGOR, J. E. RICHEY, AND F. W. ANDERSON. Pp. 160; figs. 21; pls. 8. Scotland Geol. Survey Mem., Edinburgh, 1949. *Coal mining and quarrying of road metal and freestone; geology studied by periods.*

Australia Bureau of Mineral Resources, Geology and Geophysics—Melbourne, 1950.

The Australian Mineral Industry—Graphs, 1949. H. F. PEARSON. Pp. 28.

The Australian Mineral Industry—Economic Notes and Statistics, Vol. 2, No. 3. Pp. 41.

Mining Review for the Half-Year Ended June 30, 1948. Pp. 272; numerous figures. South Australia Dept. Mines No. 88, Adelaide, 1949.

The Geology of the Plateau Tinfields—Resurvey 1945–48. R. A. MACKAY, R. GREENWOOD, AND J. E. ROCKINGHAM. **The Morphology of the Jos Plateau.** F. DIXEY. Pp. 80; pls. 5; 2 colored maps; 6 anaglyphs. Nigeria Geol. Survey Bull. 19, Kaduna, 1949. Price 12 s 6 d. *Much investigation is required, specially of unique columbite deposits.*

Hyderabad Geological Survey—Hyderabad-Deccan, 1948–1949.

Geol. Ser. Bull. 6. A Popular Geology of Hyderabad. A. M. HERON. Pp. 58. *Written for the layman.*

Jour. Vol. V, Pt. 2. Synopsis of the Purana Formations of Hyderabad. A. M. HERON. Pp. 129. *Descriptions of individual formations.*

Contributions to the Geology of Northwest Greenland, Ellesmere Island and Axel Heiberg Island. J. C. TROELSEN. Pp. 85; figs. 17; map 1. Vidensk. Undersogelser I Gronland Bd. 149, No. 7, Kobenhavn, 1950. *An account of the main geological results of the Danish Thule-Ellesmere Land Expedition 1939–1941. Physiography, structure, stratigraphy, and historical geology described.*

Manuel de Paléontologie Végétale. LÉON MORET. Pp. 230; figs. 86. Masson et Cie., Paris, 1949. *A text on paleobotany.*

Service des Mines de Madagascar—Paris, 1948.

Each of the following Explanation Notes contains from 9 to 18 pages on various parts of the geologic map of Madagascar.

Tsaramandroso; Ambovombe; Tsivory; Bekodoka; Tsihombe; Bekily; Ampanihy; Ampotaka; Manantenina; Behara Fort-Dauphin; Esira.

Section Géologie, Congrès 1947. Pp. 424. Liège, 1949. *The geology of Belgium compiled for the centennial of the Association of Engineers of the University of Liège, 1947. An introductory paper by Fourmarier on the geology of Belgium, followed by 9 papers on mineral fuels, 6 on metallic and nonmetallic ores, one on volcanics, 13 on arenaceous rocks and conglomerates, 6 on argillaceous rocks, 20 on calcareous rocks, and one on water resources.*

Etude Pétrographique et Carte Géologique du District du Congo-Ubangi, Congo Belge. B. ADERCA. Pp. 65; figs. 22; pls. 14. Inst. royal colonial belge Mém., T. XVIII, fasc. 4, Bruxelles, 1950. Price, 95 frcs. *Correlation with identical formations of the Lindi Group has permitted to determine the age of formation.*

Boletín de la Escuela Nacional de Ingenieros, Ser. III, T. 22. Pp. 72. Lima, Peru, 1949. *5 papers on engineering topics.*

Tablas para la Determinación Microscópica de Minerales Opacos. ALEJANDRO NOVITZKY. Pp. 129. Univ. Nacional de Cuyo, San Juan, Argentina, 1949. *Tables for the microscopic determination of opaque minerals based primarily on color—a method of tabulation which has passed out of use in the United States because of the difficulty in judging colors.*

Las Especies Minerales de la República Argentina. FEDERICO AHLFELD AND VICTORIO ANGELELLI. Pp. 304; figs. 27; pls. 7. Univ. Nacional de Tucumán Pub. 458, Jujuy, Argentina, 1948. *Mineral species found in Argentina.*

Geological Map of China. 5 sheets, in color, scale 1: 1,000,000. China Geol. Survey, Nanking, 1949. *Hankow, Canton, Tsingtao, Nanking, and Taiyuan sheets.*

Journal of the Chinese Geophysical Society, Vol. 1, No. 2. Pp. 128; numerous figures and tables. Nanking, 1950. Price, $0.50. *8 papers on geophysical subjects.*

Atlas Pluviométrico do Brasil, 1914–1938. Pp. 48; tbls. 5; 25 colored maps. Departamento Nacional da Produção Mineral Bol. 5, Rio de Janeiro, 1948. *Raingauge atlas of Brazil.*

Géologie et Genèse des Minerais Portugais de Chrome et de Platine. J. M. COTELO NEIVA. Pp. 19. Porto, Portugal, 1949. *Igneous rocks of Braganca have 2 to 12 gr of Pt per ton, averaging 8 gr; magnetitic amphibolite has 2 gr Pt and chloritic schist 4 gr. Chromitites from Abessedo contain 20.5% to 48% Cr_2O_3. Because of structural irregularity reserves of chromite deposits not calculated. English summary.*

Geologia dos Minérios de Ferro Portugueses—Seu Interesse para a Siderurgia. J. M. COTELO NEIVA. Pp. 60; pls. 20. Coimbra Univ. Mem. 26, Portugal, 1949. *Best iron ores are hematite, magnetite, limonite, siderite and iron-manganese ores; two biggest iron deposits are Moncorvo and Vila Cova, the latter with 16,000,000 tons measured magnetite and 20,000,000 tons inferred.*

Estudos, Notas e Trabalhos, Vol. V, Fasc. 1–2. Pp. 69; numerous figures, tables and plates. Serviço de Fomento Mineiro, Porto, Portugal, 1949. *Brief notice of magnetic investigations of some magnetite ore deposits in Alentejo, Portugal; copper formations in the Barrancos region; summary of activities; mining bibliography.*

Cenno Preliminare sulle Caratteristiche Pegmatiti Manganesifere delle Alpi Piemontesi. ANTONIO BONINO. Pp. 17; figs. 8. Torino, 1949. *Preliminary report on the manganiferous pegmatites of the Piemontese Alps.*

Zusammenhänge Zwischen Gesteinsprovinzen und Metallprovinzen. I. MIKLÓS VENDEL. Pp. 120; tbls. 9; figs. 3. Sopron, Hungary, 1949. *Relationship between rock provinces and tin and gold provinces.*

Annals of the Geological Society of Poland, Vol. 18. Pp. 356. Krakow, 1949. *Papers on zeolites; crystalline exotic blocks in the Silesian Cretaceous of the Wadowice area; foraminifera of the Flysch of the Polish Carpathians; microfauna of the Lower Cretaceous near Tomaszów Mazowiecki; problems of stratigraphy of marine Triassic in Cracow area; Lower Tortonian at Benczyn near Wadowice; dolomitization of Jurassic limestones near Cracovie.*

SCIENTIFIC NOTES AND NEWS

CHARLES PIGGOT, Scientific Attaché at the American Embassy in London, was one of the American observers to attend the Commonwealth Advisory Committee on Defense Science in Cambridge, England, the week of July 3. Dr. Piggot is also a former member of the Research and Development Board's staff, where he served as Executive Director of the Committee on Geophysical Sciences. During World War II, he served in the U. S. Navy with the rank of captain. He was active in the organization and technical direction of the Mine Disposal School and Service and the Navy Bomb Disposal School and Service. He also organized and supervised the Ordnance Investigation Laboratory devoted to the development of techniques for opening or disposing of hazardous explosive ordnance.

ROBERT A. MACKAY has resigned from the Atomic Energy Section of the Geological Survey and has taken a position with the Mond Nickel Company Limited. He will continue consulting work for certain West African Companies.

C. A. BOTSFORD, who returned in December from mine examinations in India, Burma, and Siam, has gone to Rome as consultant for the ECA Italian Mission, with headquarters at the American Embassy.

ROBERT H. CARPENTER, on leave of absence from the geology department of the Colorado School of Mines, has gone to San Juancito, Honduras, as consultant in charge of the geological examination of the Rosario properties of the New York & Honduras Rosario Mining Co.

PATRICK M. HURLEY, assistant professor at MIT, has been appointed executive officer of the geology department there.

CARREL B. LARSON, who for the past several years has been minerals attaché to the U. S. Embassies in several South American countries, recently accepted the position of assistant general manager of Patiño Mines and Enterprises, Catavi, Bolivia.

ESPER S. LARSEN has been made assistant chief geologist of the U. S. Bureau of Mines.

H. J. R. WAY has been appointed director of the Swaziland Geological Survey, Mhabane, Swaziland, S. Africa.

RUSSELL G. WAYLAND has been appointed acting U. S. Chairman of the Combined Coal Control Group, Office of the U. S. High Commissioner for Germany. The work remaining before the Group covers the approval and release of Marshall Plan funds to the individual development, construction, and reconstruction projects of the Ruhr coal mining industry, and the break-up of the corporate structure of old Ruhr combines and the establishment of new independent coal mining companies.

F. T. M. WHITE has resigned from His Majesty's Colonial Mines Service and has accepted the appointment of professor of mining engineering in the University of Queensland, Brisbane, Australia. The chair is a new one and he is its first incumbent.

JOSEPH L. GILLSON, of the Development Department of the Du Pont Company, has been nominated to be a vice president and director of the American Institute of Mining and Metallurgical Engineers for 1951. Dr. Gillson has held several important posts with the AIME in the past. In 1947 he was chairman of its Industrial Minerals Division and until recently was chairman of its Committee on Democratization. He is also a fellow of the Mineralogical Society of America, serving as that society's vice president in 1932, and of the Geological Society of America. He is a director of the American Geological Institute and for three years was on the Council of the Society of Economic Geologists.

HARRY H. HESS, mineralogist on leave as an exchange professor at the University of Cape Town, South Africa, has been appointed to succeed Dr. ARTHUR FRANCIS BUDDINGTON as chairman of the Department of Geology at Princeton University. Dr. Buddington is relinquishing his administrative duties, after fourteen years as chairman, in order to devote more time to research. He will continue his teaching.

The INSTITUTION OF MINING AND METALLURGY has commenced the publication of monthly abstracts of world literature on economic geology and mining (excluding coal), mineral dressing, extraction metallurgy (excluding iron but including refining), and allied subjects of interest. Annual subject and author indexes will be issued. For the time being *I. M. M. Abstracts* will be published as part of the Bulletin of the Institution and will be issued free to Members and Subscribers. The subscription rate for the Bulletin including I. M. M. Abstracts is 3.0.0. per annum (12 monthly issues) and enquiries should be addressed to the Institution at Salisbury House, Finsbury Circus, London, E. C. 2, England.

The Industrial Minerals Division of the American Institute of Mining and Metallurgical Engineers will hold its annual Fall Regional Meeting in Norman, Oklahoma, on October 17 to 20, where the Oklahoma Geological Survey will be their host. At the technical sessions on October 17 and 18 many papers will be presented, among which are two on the titaniferous magnetite. Plans are being made for an active discussion of the titanium papers by men familiar with the occurrence of ilmenite deposits. Dr. Hugh D. Miser, of the U. S. Geological Survey, will be the dinner speaker. Field trips will be held in the Arbuckle Mountains, south-central Oklahoma, on October 19 and 20.

SIDNEY PAIGE retired from the Research & Development Board, Department of Defense, Washington, D. C., on January 1, 1950, and will engage in consulting practice in New York City. He may be addressed at Alpine, N. J., or Box 6, Schermerhorn Hall, Columbia University, Broadway at 116th Street, New York City. Mr. Paige is a Visiting Professor of Engineering Geology at Columbia University.

HENRI J. DE WIJS is now professor in petroleum and mineralogy at the Technical University, Delft, Holland.

W. C. PAGE was elected vice-president and general manager of western operations, U. S. Smelting, Refining & Mining Co. He formerly held the position of general manager of western operations.

FRANCIS A. THOMSON, president of the Montana School of Mines, was awarded the Distinguished Achievement Medal of the Colorado School of Mines.

The American Institute of Mining and Metallurgical Engineers has recently organized a new professional division entitled The Mining, Geology, and Geophysics

Division. The chairman is P. J. Shenon, University of Utah, Salt Lake City, Utah, and the Secretary is James K. Richardson, Kearns Building, Salt Lake City, Utah. This new division embraces three subdivisions—one devoted to mining, the second to geology, and the third to geophysics. The Chairman of the Geology Subdivision is also P. J. Shenon, and the Secretary is James K. Richardson. Its field will be the same as the former Mining Geology Committee of the Institute—namely, the economic geology of metal and nonmetallic mineral deposits. The Geophysics Subdivision is under the chairmanship of James B. Macelwane, St. Louis University, 3621 Olive St., St. Louis 8, Mo., with Sherwin F. Kelly, Amawalk, N. Y., as Secretary. The scope of the Geophysics Subdivision includes the application of geophysical engineering techniques not merely to metal mining but to exploration for nonmetallic minerals, to the measurement of overburden, to the location of limestone, gravel and other deposits not exposed at the surface, to the search for water supplies and the mapping of the water table. Each of these subdivisions welcomes submission of papers in its field. These, when accepted as technical papers of the Institute, will subsequently be published in *Mining Engineering*.